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CONTENTS

	Pages
Bennett, E. B. Some oceanographic features of the northeast Pacific Ocean during August 1955	565–633
Pickard, G. L., and G. Keith Rodgers. Current measurements in Knight Inlet, British Columbia	635–678
McBride, J. R., R. A. MacLeod and D. R. Idler. Proximate analysis of Pacific herring (*Clupea pallasi*) and an evaluation of Tester's "Fat Factor"	679–684
MacLeod, Robert A. Condensed fish solubles. A review of its preparation and properties	685–694
Lindsey, C. C., T. G. Northcote and G. F. Hartman. Homing of rainbow trout to inlet and outlet spawning streams at Loon Lake, British Columbia	695–719
Parker, Robert R., and Peter A. Larkin. A concept of growth in fishes	721–745
Belinski, E., and H. Foucher. The effect of sodium chloride on proteolysis and on the fate of amino acids present in the muscle of codfish (*Gadus callarias*)	747–754

(*Continued Overleaf*)

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NOTES

Distribution of a lipase enzyme in lingcod fillets and the effect of low temperature storage on its activity. By J. D. WOOD 755–757

The first record of a northern blennioid fish, *Plectobranchus evides* Gilbert (family Stichaeidae), in British Columbia waters. By W. E. BARRACLOUGH 759–760

A record of the anomuran crustacean *Emerita analoga* (Stimpson) from British Columbia. By T. H. BUTLER 761

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Some Oceanographic Features of the Northeast Pacific Ocean during August 1955[1,2]

By E. B. Bennett[3]

Fisheries Research Board of Canada
Pacific Oceanographic Group, Nanaimo, B.C.

CONTENTS

	Page
Introduction	566
I. Structure and Physical Properties of the Water	567
The Temperature Field	
Characteristics of the vertical distribution of temperature	569
Vertical sections of temperature	575
Lateral distributions of temperature	578
The Salinity Field	
Characteristics of the vertical distribution of salinity	584
Vertical sections of salinity	586
Lateral distributions of salinity	589
The Mass Field	
Characteristics of the vertical density structure	594
Vertical sections of density	595
Lateral distributions of density	598
Summary and Conclusions	602
II. Currents and Volume Transport	605
Method	605
Choice of the equipotential surface	605
Dynamic height anomalies	607
Geostrophic current and volume transport	610
Velocity Profiles	612
Influence of local wind	612
Possibility of Abyssal Current	616
Volume Transport	618
Influence of surface wind	620
Comparison with conditions in August 1950	621
Vertical motion at the null flow line	622
Intensification of Alaskan Stream	623
Current in the vicinity of Sanak Island	626
Influence of bottom topography	628
Summary and Conclusions	632
Acknowledgment	632
References and Data Sources	632

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[2]Based on a thesis accepted by the University of British Columbia in partial fulfillment of the requirements for the degree of Master of Arts.
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ABSTRACT

Physical oceanographic data from the international NorPac survey of August 1955, in the area north of Lat. 45°N and east of Long. 161°W, were examined. The temperature, salinity, and density distribution and structure from the surface to 2000 m are discussed.

The temperature structure showed an isothermal layer to about 30 m depth, a marked thermocline to about 100 m depth, a temperature inversion in most of the area, and below this a gradual temperature decrease into the abyss. At all depths the water was coldest in a "cold core" centered about 100 miles south of Kodiak and the Shumagin Islands. From there the temperature increased at each level in all directions.

The salinity structure showed an isohaline layer to about 100 m depth, a marked halocline to about 200 m depth, and below this the salinity increased slightly into the abyss. The salinity structure did not coincide with the temperature structure.

The density structure showed an isopycnal layer to about 30 m depth, a pycnocline associated with the thermocline, a second isopycnal layer, a second pycnocline associated with the halocline, and below this the density increased slightly into the abyss.

Variations in these structures throughout the region are discussed in some detail.

There is no horizontal isosteric level in the 2000 m of depth. It is concluded that there is no level of "no net motion" in this range, but a reference level of 2000 decibars (db) for dynamic calculations is more acceptable than the usual 1000-db level. A new procedure is introduced to extend the reference level into the bottom in near coastal areas,

The geostrophic currents were calculated. There was a major latitudinal drift from the west into the central part of the area. It veered northward and continued around the Gulf of Alaska, forming the Alaska Gyral, and left the area to the westward, as an intensified current (Alaskan Stream) close along the Alaskan Peninsula. This intensification is probably due to conservation of absolute vorticity through changing latitude.

The circulation pattern extended to at least 2000 m depth, and probably to the bottom. It transported about 17 million m^3 of water per second. There were a number of eddies in the system, some of which were observed on earlier surveys.

The major flow pattern was not wind-generated within the region. The influence of local winds was limited to the upper 200 m of depth. In some areas it aided the flow, and in others retarded it.

There is evidence to show that two chains of seamounts influenced the current pattern according to the Sverdrup concept. Since the major portion of these is below 2000 m depth it is concluded that currents exist in the abyss, in essentially the same direction as at the upper levels.

INTRODUCTION

FROM LATE JULY TO EARLY SEPTEMBER OF 1955 the international NorPac oceanographic survey gathered data from the Pacific Ocean, north of Lat. 20°N. Since that time the Pacific Oceanographic Group of the Fisheries Research Board of Canada has undertaken several expeditions in further study of that region north of Lat. 40°N, and east of Long. 175°W. The intended result of these surveys is a complete description, both in time and space, of the oceanography of the Gulf of Alaska and adjacent waters. This report constitutes an integral part of that description and follows the initial preliminary assessment by Tully and Dodimead (1957).

This thesis concerns a description of the water structure and an interpretation of the magnitude of the volume transport of water interpreted from the 1955 NorPac data (Fleming, 1956; Pacific Oceanographic Group, 1956; Scripps Institution of Oceanography, 1956).

The area of investigation (hereafter referred to as the "region") (Fig. 1) is that part of the northeast Pacific Ocean north of Lat. 45°N, and east of Long. 161°W. The oceanographic stations included are:

(a) University of Washington Stations 110-1 to 110-69. For facility, the cruise number will be dropped and these stations will be referred to as U of W Sta. 1, etc.

(b) Pacific Oceanographic Group Stations 1 to 43 and 66 to 85 (POG Sta. 1, etc.)

(c) Scripps Institution of Oceanography Stations 1 to 11 (SIO Sta. 1, etc.)

Figure 2(A) shows the location of these stations.

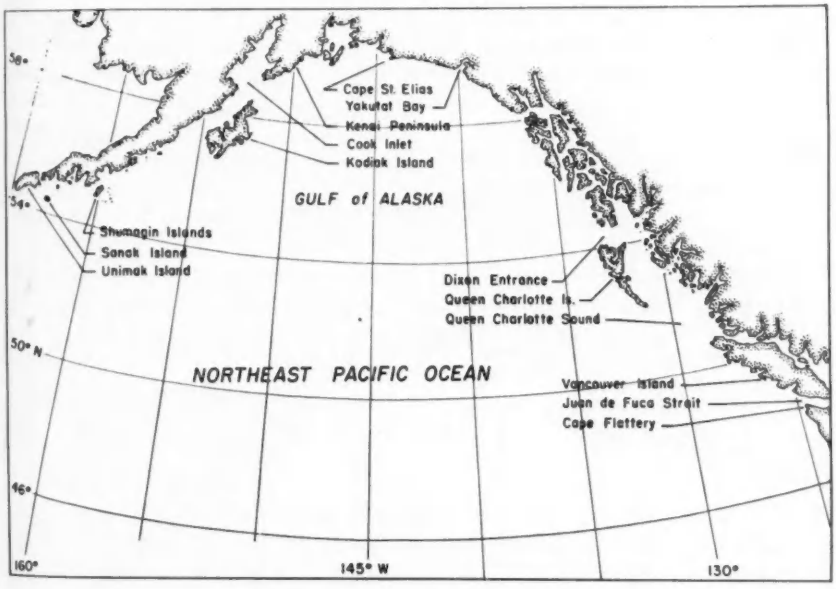

FIG. 1. Place names in the region.

For the preliminary discussion of water structure, all 142 stations were used where possible, but in the section on volume transport only the 48 stations were used where the depth of observation reached, or could be extrapolated to, 2000 m.

I. STRUCTURE AND PHYSICAL PROPERTIES OF THE WATER

The calculated geostrophic volume transport of water depends on the pressure (density) field. In turn, the density field is computed from the observed fields of

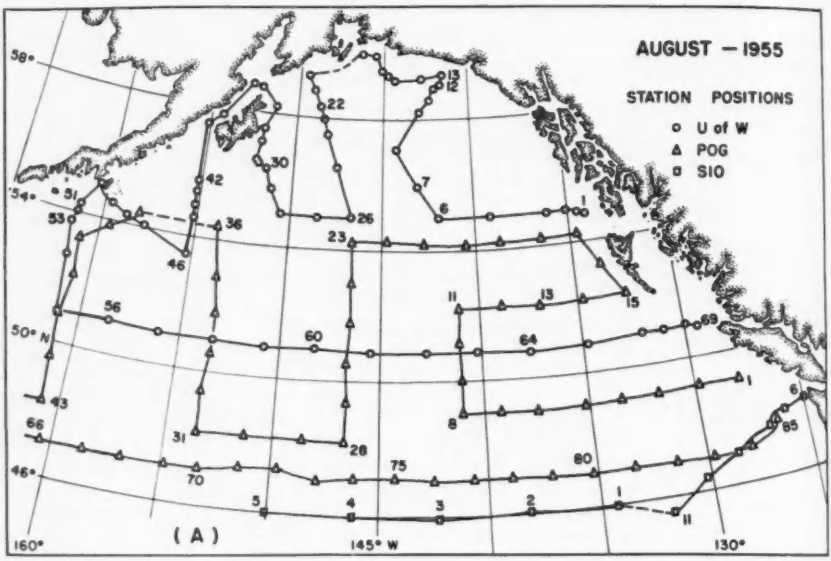

FIG. 2(A). Station positions.

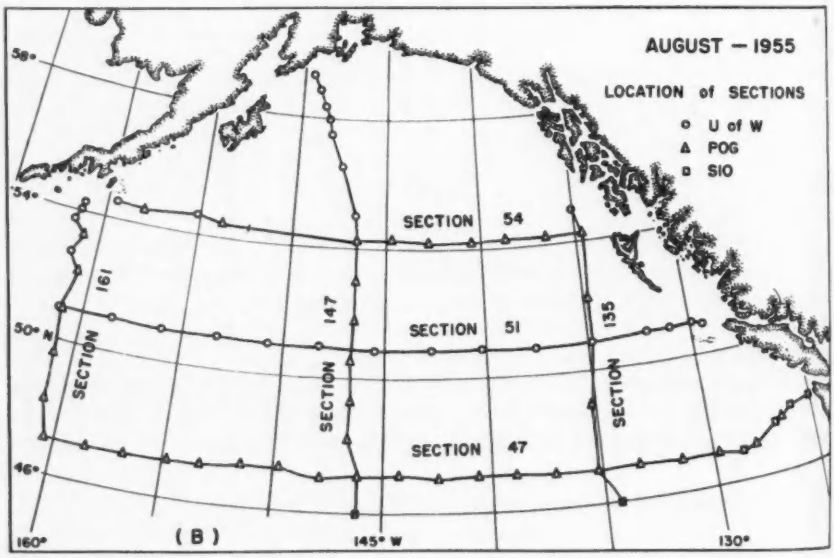

FIG. 2(B). Location of sections.

temperature and salinity. In that which follows, the essential features of the temperature and salinity fields which existed in the region during August 1955 are discussed, after which the corresponding density field is reviewed.

Three aspects of each field are investigated. First, the characteristics of the distribution with depth of each property are discussed at a representative station and then for the whole region. Next, the distribution of that property in six vertical sections is considered. Lastly, the lateral distribution of the property at several depths is reviewed.

The six traverses of the region and the included stations chosen for the vertical sections are shown in Fig. 2(B). The sections are centered approximately on Lat. 54°20′N, 51°00′N, and 47°00′N, and on Long. 161°00′W, 147°W, and 135°W. For convenience, these sections are named Sect. 54, 51, 47, 161, 147, and 135, respectively. For any section the drawing of isopleths of any property was accomplished by reading, from the property vs. depth curve (station plot) for each station of the section, the depths at which the isopleths occurred. Then the depths common to one isopleth were joined by a smooth curve. For temperature sections, bathythermograms, in the role of supplementary data, were used to place isotherms between stations, as well as to define the vertical temperature structure between serial observations at one station.

The surfaces selected for the discussion of the lateral distribution of a property are 10, 50, 100, 200, 400, 600 and 1000 m depth. Values for each property at any depth were derived from the corresponding station plots.

Both the vertical sections and the lateral distributions are dependent on the station plots for values of any property. Therefore the three representations of data are concurrent, and as such any "smoothing" of one representation had a corresponding effect in the other two representations, but the serial observations of the parent station plot were never violated.

The Temperature Field

CHARACTERISTICS OF THE VERTICAL DISTRIBUTION OF TEMPERATURE. A temperature – depth curve typical of these data from the northeast Pacific Ocean is shown in Fig. 3. From the surface down, the curve exhibits in order: a shallow isothermal layer; a shallow layer in which temperature decreases rapidly (thermocline); a layer in which a temperature inversion may occur; a lower zone in which temperature decreases gradually into the abyss. Each layer is further discussed below.

The surface isothermal layer is the result of mixing by the surface wind. Figure 4 shows the depth of this layer over the region. The observed range of depth was 0 to 52 m, and the average of observed values was about 23 m. Maximum layer depths occurred at Lat. 51°N and Long. 150°W. South and east of this was an area which had a surface layer depth of less than 10 m.

The bottom of the surface isothermal layer (Layer Depth) marks the top of the thermocline. From there temperature decreased rapidly with depth to either a "minimum" value or to an "inflection point" value. The temperature decrease

in the thermocline is defined as the difference between the temperature at the bottom of the surface isothermal layer, and the temperature of either the minimum point or inflection point of the temperature–depth curve, for each station. Illustrated in Fig. 5 is the magnitude of this difference over the region. In the

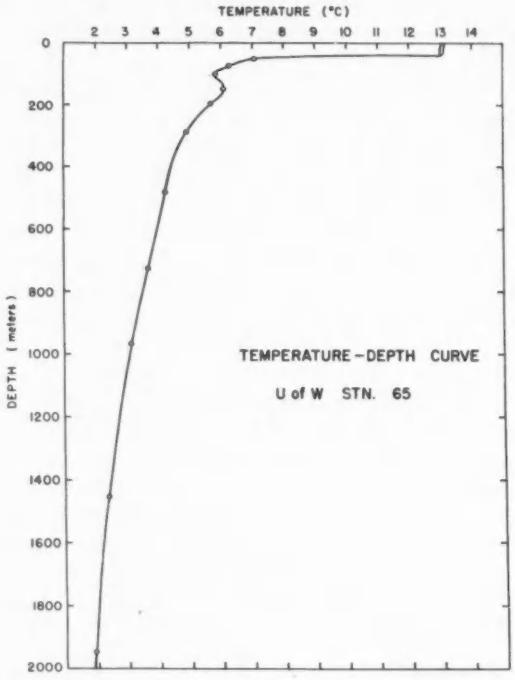

FIG. 3. Temperature–depth curve at U of W Sta. 65.

center part of the region, this decrease was about 6.5 C°. Southward, the temperature differences were larger, exceeding 9.0 C° at the limit of the region. Northwestward of the center, the difference first became larger, reaching a maximum of 8.3 C° about 200 miles southeast of Kodiak Island, and then became smaller to the coast. The average of all observed values of the temperature decrease in the thermocline was 6.9 C°.

The bottom of the thermocline was usually marked by a temperature minimum, i.e., in most cases there was a temperature increase below the thermocline. The origin of this temperature has been discussed by Tully (1957), from which the following is quoted.

> "In March, towards the end of winter the upper zone waters are isothermal and at a minimum temperature, somewhat colder than the top of the deep zone. As the season advances the surface waters are warmed by vernal heating. This process may be regarded

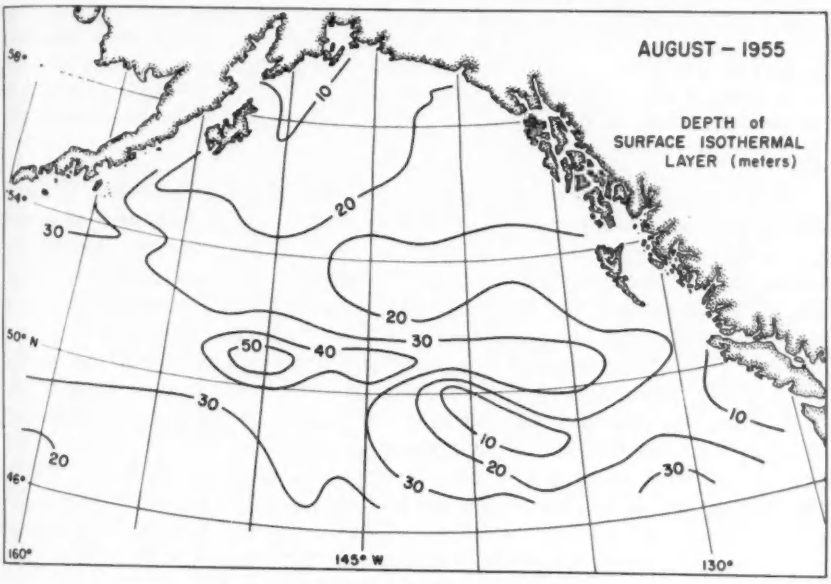

FIG. 4. Depth of surface isothermal layer.

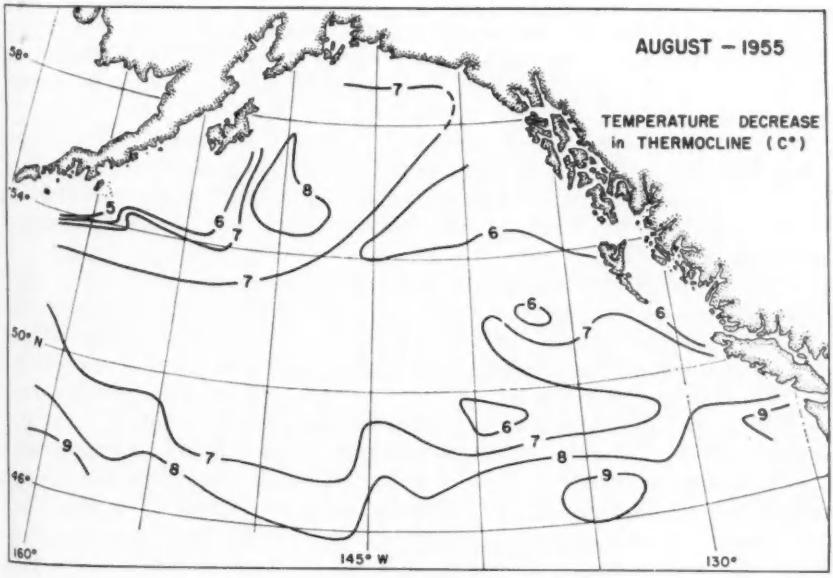

FIG. 5. Temperature decrease in thermocline.

as the accumulation of heat from successive afternoon effects and wind mixing . . . The warm upper zone continues to increase through summer to mid-September. However, in the autumn the surface cools and violent winter storms mix the waters. In this process the upper zone cools but continues to become deeper. Eventually its boundary intercepts the remnants of the previous winter boundary, and finally the characteristic late winter structure is formed."

Of the 111 stations examined which were considered deep enough to allow development of the above-described feature termed the dichothermal structure (e.g. Uda, 1935), 102 (92%) exhibited this structure. Therefore, this is a characteristic feature of the vertical temperature structure of the water of the region. The temperature–depth curves of the other 9 stations had an inflection point at approximately the same depth at which the dichothermal structure usually appeared. The topography of the relative temperature minimum is illustrated in Fig. 6(A). By definition, this is also the topography of the lower limiting depth of the thermocline. The cross-hatched areas of Fig. 6(A) indicate where the dichothermal structure was absent. The minimum depth at which this feature was observed was 60 m, and that was 130 miles east of Kodiak Island. North of Lat. 52°N, the depth of the temperature minimum was less than 125 m, with the marked exception of the northeast part of the region. The depth of the temperature minimum surface generally exceeded 125 m over the southern half of the region. A bi-tongue area occurred in which depths exceeded 150 m.

Figure 6(B) shows the isotherm pattern on the temperature minimum surface. The minimum values were less than 3.5°C, and occurred in a small tongue about 100 miles south of the Shumagin Islands. From this cold center toward the coast, and toward the southern limit of the region, increasingly higher values of the temperature minimum were found. This is shown markedly by the isotherms of 4.0°C, 4.5°C, 5.0°C, and 5.5°C. At the southeast corner or the region the values of the temperature minimum were greater than 7.0°C.

Since, in Fig. 6(B), the isotherms of 3.5°C, 4.0°C, 4.5°C, and 5.0°C define a cold center or cold core, such a pattern of isopleths is termed the "core" pattern.

Below the dichothermal layer a relative maximum temperature existed. Shown in Fig. 7(A) is the topography of this maximum temperature. The observed range in depth was from 95 to 215 m.

The isotherms on the maximum temperature surface are illustrated in Fig. 7(B). The core pattern was expressed by the 4.5° and the 5.0°C isotherms and was well supported by those of 5.5° and 6.0°C. Toward the southeast corner of the region the maximum temperature increased, exceeding 7.0°C at the corner.

The difference between the relative maximum and minimum temperatures over the region is illustrated in Fig. 8. The maximum difference of 1.08 C° occurred at U of W Sta. 29, about 120 miles south and east of Kodiak Island. Other observed large differences were 0.93 C° at U of W Sta. 10, located about 100 miles southwest of Yakutat Bay; 0.91 C° at U of W Sta. 6 and 8; and 0.81 C° at POG Sta. 14, located west of the Queen Charlotte Islands. The difference was less than 0.2 C° at the coast except off Vancouver Island and Cape Flattery where it was greater than 0.5 C°. Also in the south central part of the region the difference

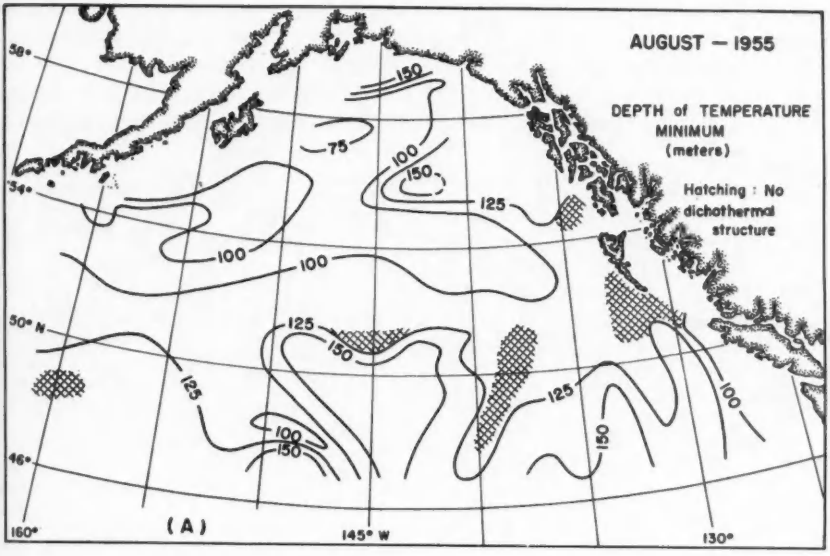

FIG. 6(A). Depth of temperature minimum.

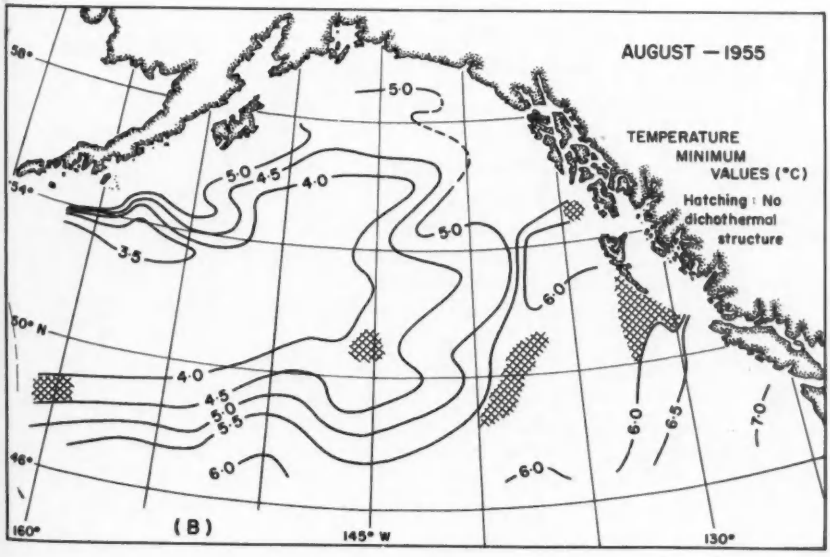

FIG. 6(B). Temperature minimum values.

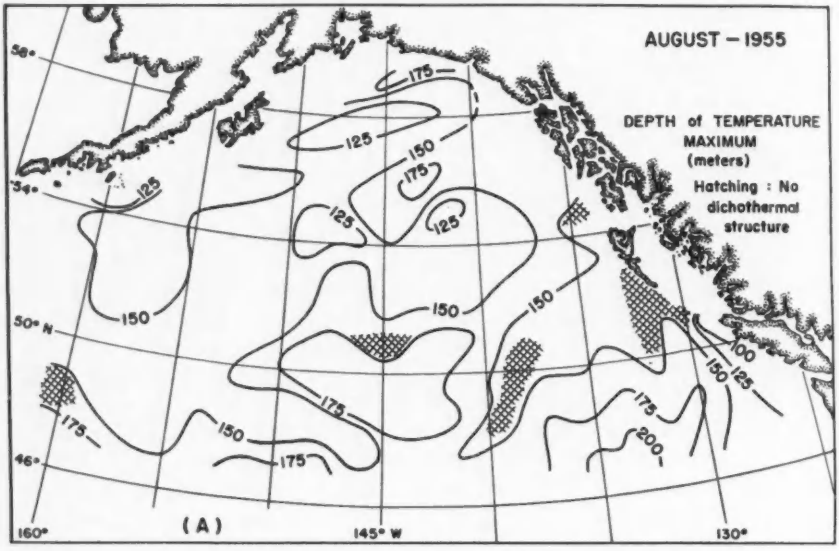

FIG. 7(A). Depth of temperature maximum.

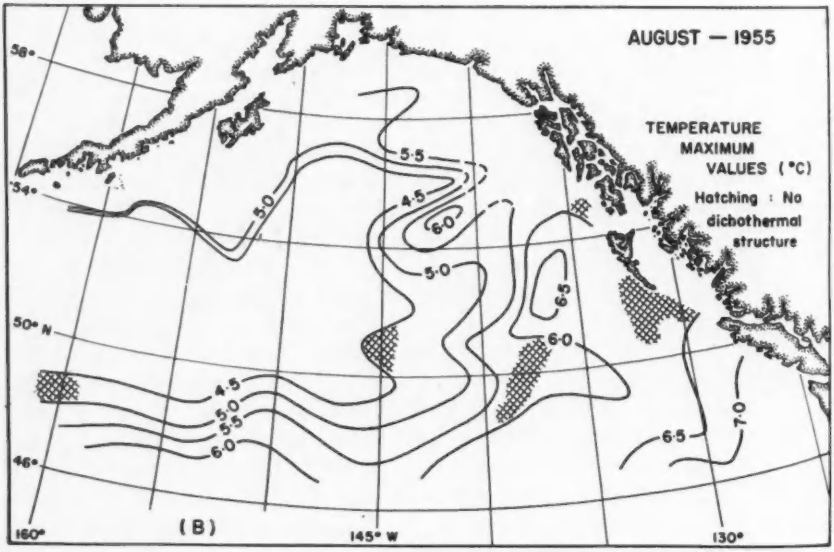

FIG. 7(B). Temperature maximum values.

was less than 0.2 C°. The average value of the observed differences was 0.33 C°. The variation of differences between the maximum and minimum temperature was too large to conclude that the vertical structure is the result of only vernal heating and wind mixing. The several isolated large differences must have been due to some process such as upwelling or shearing in the water column. Similarly,

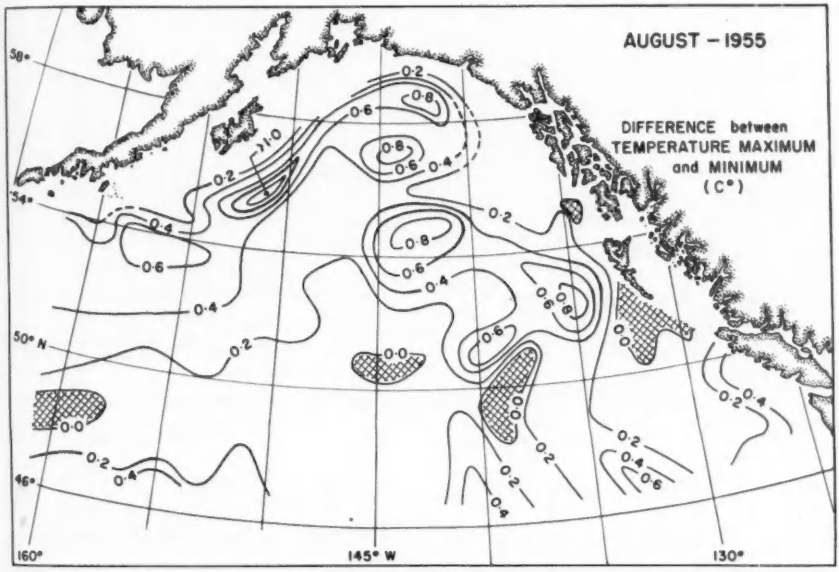

FIG. 8. Difference between maximum and minimum temperatures.

the absence of a dichothermal structure must also have been a result of motion in the water column. It is concluded that large differences between the temperature minimum and maximum values (differences of the order of 1 C°) and the absence of dichothermal structure are both non-characteristic.

Below the relative maximum temperature a smooth temperature decrease with depth occurs, at least to 3900 m as indicated by the temperatures of U of W Sta. 55.

VERTICAL SECTIONS OF TEMPERATURE. Figures 9(A) through 9(F) illustrate the distribution of temperature in the six selected sections.

All sections had a well-delimited thermocline which occurred at 25 to 50 m depth. The minimum temperature at the top of the thermocline was about 10°C for most sections, but was higher along the eastern and southern limits of the area. At the southern side of the region the temperature at the top of the thermocline reached 14°C, and 100 miles off Cape Flattery was as much as 16°C.

The temperature at the bottom of the thermocline was a minimum in the center and at the western side of the region.

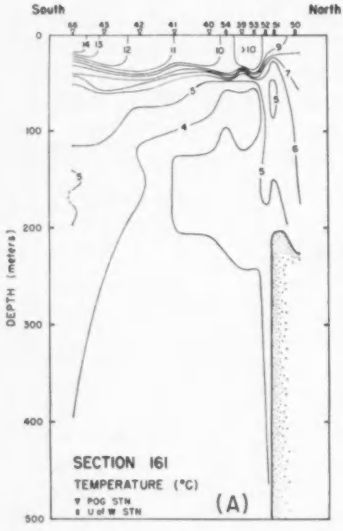

FIG. 9(A). Temperature — Section 161.

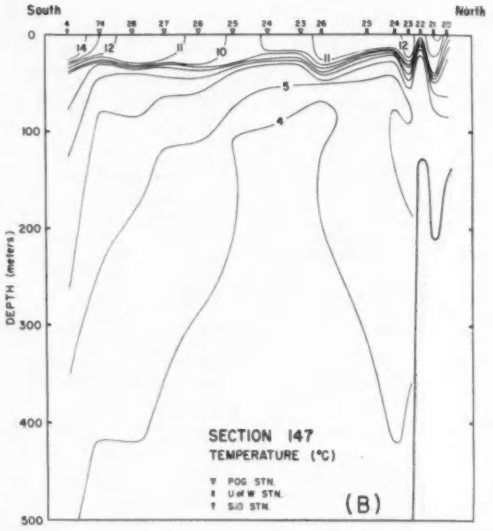

FIG. 9(B). Temperature — Section 147.

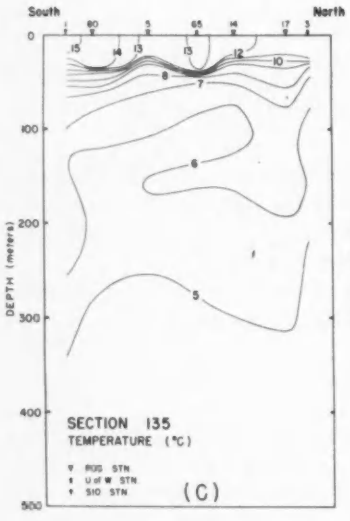

FIG. 9(C). Temperature — Section 135.

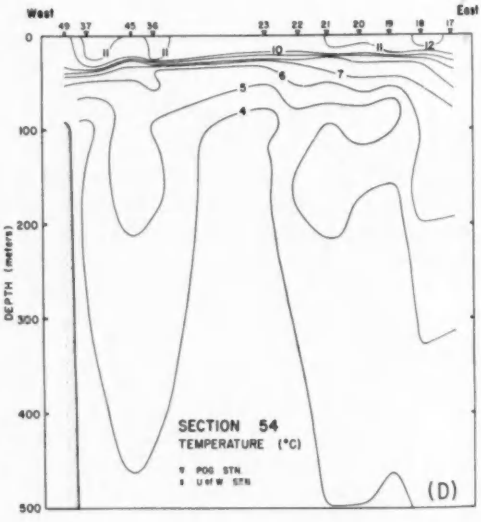

FIG. 9(D). Temperature — Section 54.

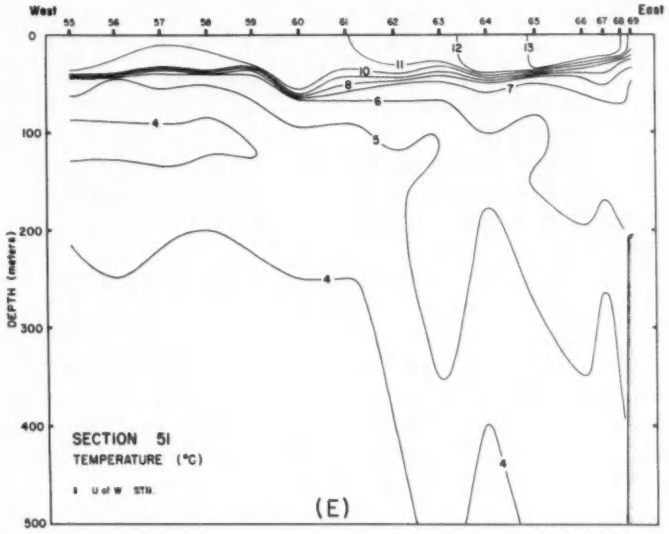

FIG. 9(E). Temperature — Section 51.

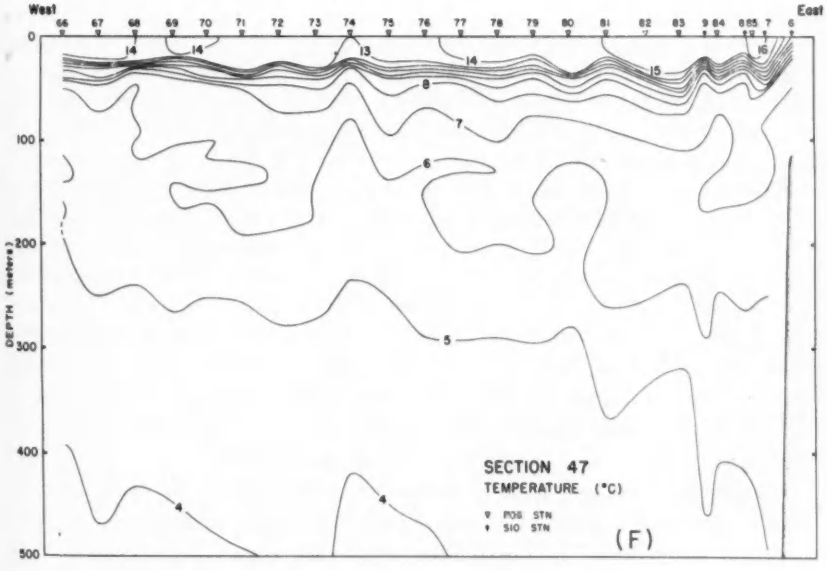

FIG. 9(F). Temperature — Section 47.

In the sections along Long. 161°W and 147°W, the isotherms below the thermocline rose from south to north until some shoalest depth was reached within 200 miles of the edge of the continental shelf. Closer to, and at the shelf, the isotherms descended rapidly. This is best exemplified by the 4°C isotherm in both sections. In a south-to-north traverse of the sections, the 4°C isotherm rose and then fell at least 350 m.

The rising and falling of isotherms below the thermocline did not occur in Sect. 135. Furthermore, nowhere in Sect. 135 was the temperature less than 4°C above 500 m. Thus the water represented in this section is about 1°C warmer than that of the other meridional sections.

The section along Lat. 54°N had a temperature structure similar to those of Sect. 161 and 147, except that adjacent to the continental slope the isotherms below the thermocline fell to seaward. However, further east the 4°C isotherm rose about 350 m. From mid-section, temperature at any depth increased eastward.

In Sect. 51 and 47 the rising and falling of isotherms did not occur (except for meanderings caused by the dicho- and mesothermal structure). Instead, the temperature at any depth generally increased from west to east. This accounted for Sect. 135 being the warmest meridional section.

At the east end of Sect. 51 and 47 the thermocline rose and, in the case of the latter section, intersected the surface. Indications are that a few miles east of U of W Sta. 69 of Sect. 51 the thermocline also reached the surface. The upward slope of the thermocline toward the Canadian coast has been discussed by Doe (1955). It was observed in 1950 and in 1951 and it occurred in the vicinity of the continental slope.

LATERAL DISTRIBUTIONS OF TEMPERATURE. The horizontal temperature distributions at various depths are shown in Fig. 10(A) through 10(H). At each depth, south of Lat. 50°N on the western portion of the region, the isotherms were essentially zonal. Further east, isotherms turned north and then ran approximately parallel to the coast line.

The temperature distribution at 10 m depth was of marked zonal character south of Lat. 50°N and between Long. 160°W and 140°W. The southern limit of the region had temperatures greater than 14°C. Still higher temperatures occurred in the southeastern part of the region, with the maximum observed temperature, 16.37°C, located about 75 miles southwest of Cape Flattery. The 11°C isotherm had the core shape, but south of the Shumagin Islands the isotherm turned north and east and ended at about Lat. 54°N. A tongue of relatively high temperature water was present in the northern part of the region. From the warm tongue to the coast of the Alaska Peninsula temperatures decreased. The minimum observed temperature, 8.62°C, was located near the Shumagin Islands.

On the 50-m surface, the 6°C isotherm had the shape of the "core" pattern. From the core area to Alaska and Kenai Peninsulas higher temperatures occurred, in contrast to the 10-m distribution. Southward and southeastward from the core area the temperatures increased. Only off Vancouver Island did relative minimum temperatures less than 8°C exist. Two areas of relative maximum temperature

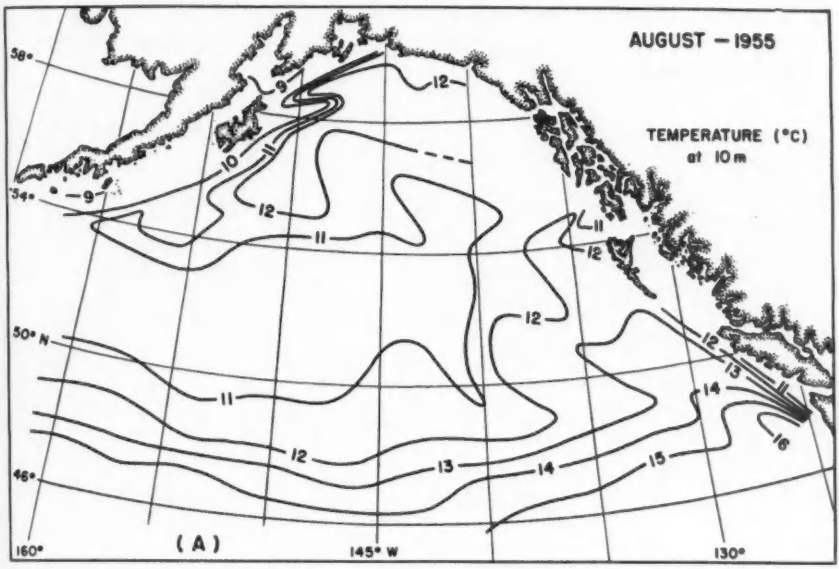

FIG. 10(A). Temperature at 10 m depth.

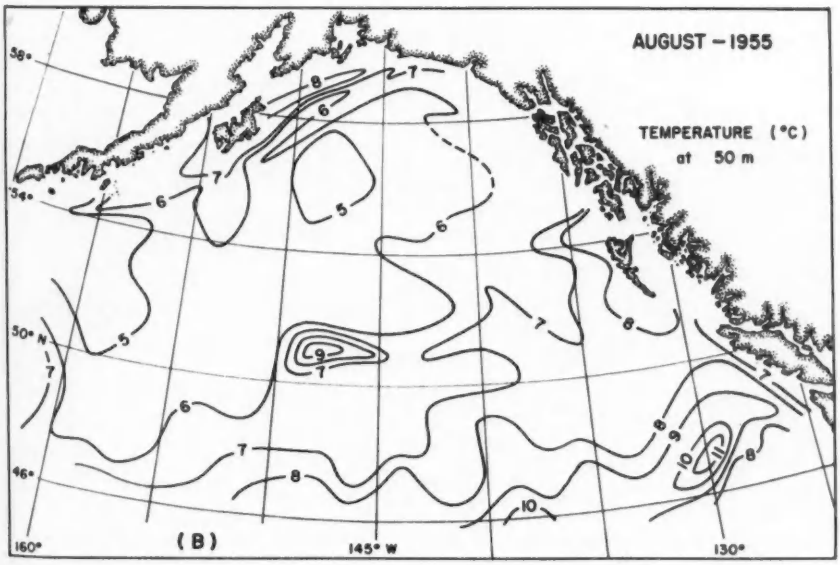

FIG. 10(B) Temperature at 50 m depth.

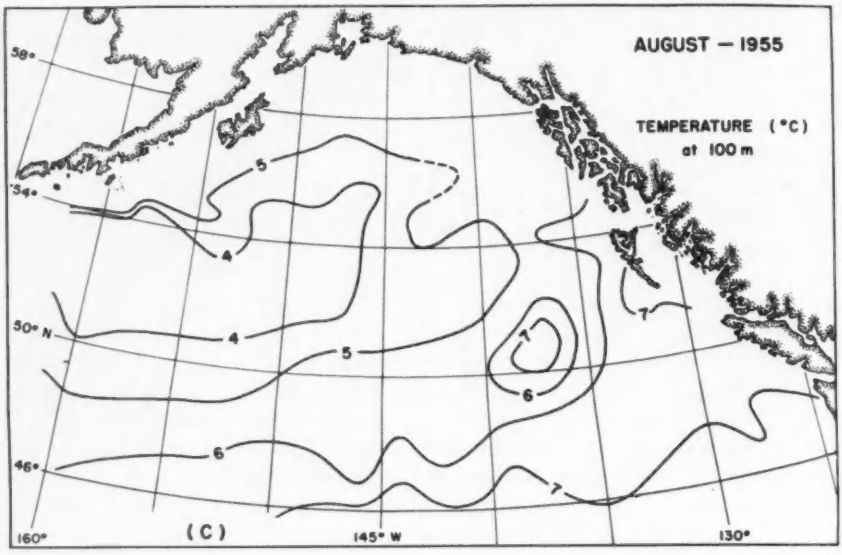

FIG. 10(C). Temperature at 100 m depth.

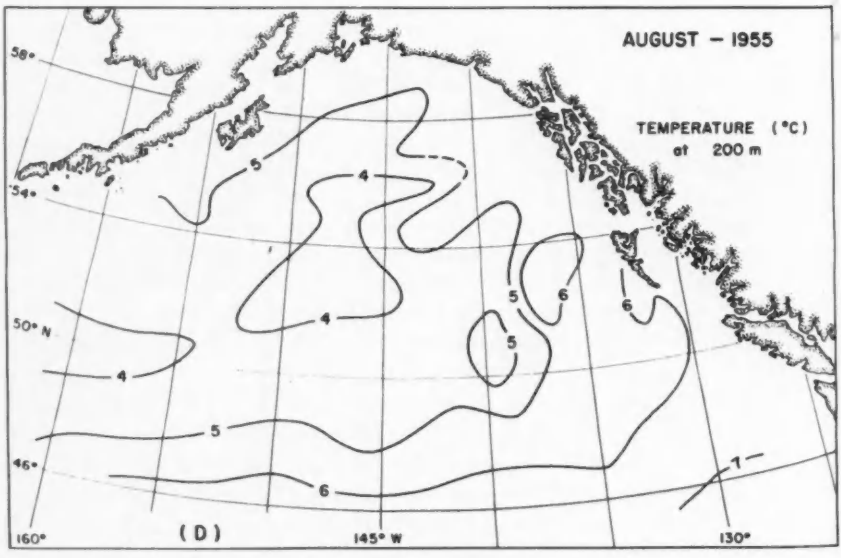

FIG. 10(D). Temperature at 200 m depth.

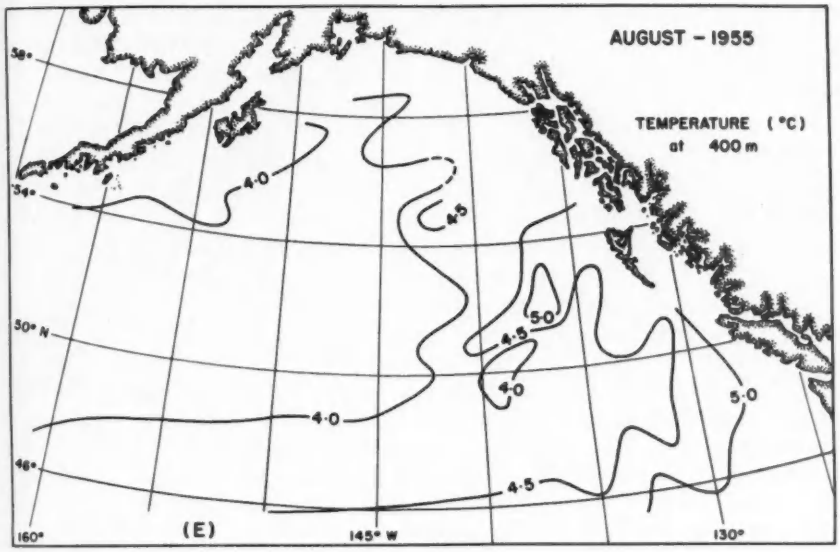

FIG. 10(E). Temperature at 400 m depth.

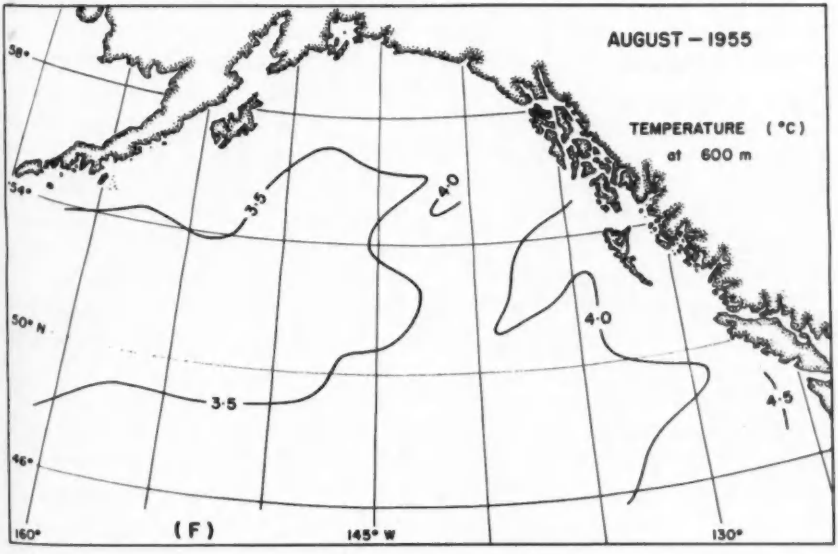

FIG. 10(F). Temperature at 600 m depth.

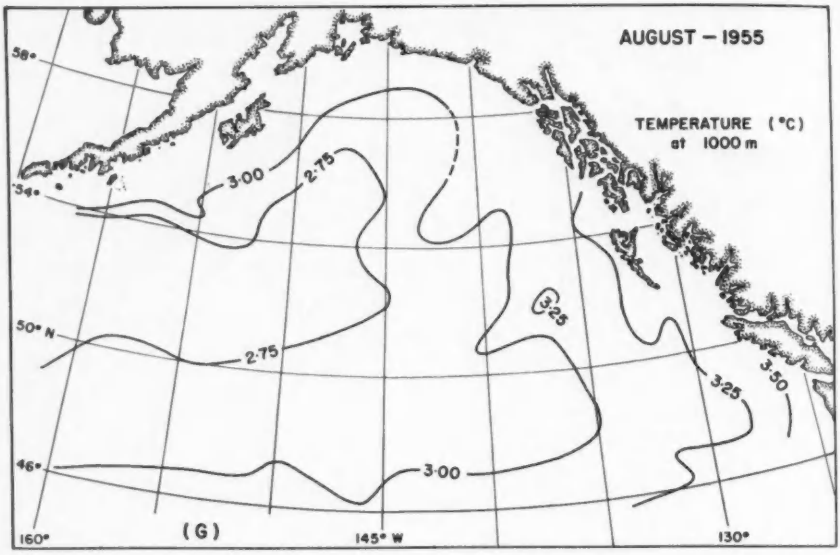

FIG. 10(G). Temperature at 1000 m depth.

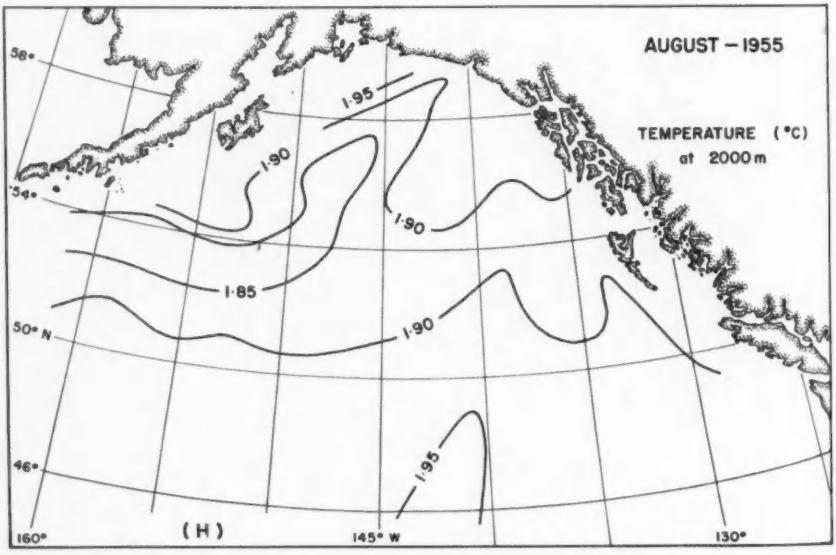

FIG. 10(H). Temperature at 2000 m depth.

were present. One was located near the center of the region and had a maximum observed temperature of 9.80°C; the other was located south and west of Cape Flattery, within the 9°C isotherm tongue.

At 100 m depth the core pattern was well expressed by the 4°C and 5°C isotherms. The minimum observed temperature was 3.74°C. North, east, and south of the core area, temperature increased, with maxima, greater than 7°C, occurring at the southeastern limit of the region and next to the Queen Charlotte Islands. The maximum observed temperature, 7.99°C, occurred at U of W Sta. 64, located southwest of the Queen Charlotte Islands, and this produced an area of relative maximum temperature.

At 200 m depth the isotherm pattern did not represent the core pattern as well as at 100 m. In general, the water in the core area was warmer than at 100 m depth. A tongue of water of temperature slightly less than 4°C extended from the western boundary of the region to about Long. 154°W. In the center of the region there was an area of temperature less than 4°C. Here the minimum observed value was 3.85°C. The 5°C isotherm was essentially zonal along the southern side of the region, as far as Long. 140°W, where it turned north. At Lat. 55°N, the 5°C isotherm turned west and south and back again to form a tongue of relatively warm water, in the same manner as at 100 m. At the center station of this tongue, U of W Sta. 6, temperature was 5.61°C at 200 m depth, while at the neighboring U of W Sta. 7 the value was 3.92°C.

At 400 m depth temperatures were less than 4.0°C in most of the central and western portions of the region. The minimum observed value was 3.61°C. The 4.0°C isotherm, which turned north at about Long. 143°W, swung east at Lat. 55°N and back again further north, thus forming a tongue of relatively cold water. The tongue included U of W Sta. 7 which had the temperature 3.78°C. In contrast, U of W Sta. 6 had a value of 4.60°C, and this showed as a relative maximum bounded by the 4.5°C isotherm. Off the Canadian coast, the 4.5°C isotherm curved to and from the coast to form a series of tongues. The tongue best defined by this isotherm included POG Sta. 13 where occurred the relative maximum temperature of 5.16°C. The maximum observed value was 5.48°C, and was located about 50 miles southwest of Cape Flattery.

On the 600-m surface, the core area had temperatures less than 3.5°C. The minimum observed value was 3.27°C. The maximum observed value was 4.55°C, and was located about 50 miles southwest of Cape Flattery.

At 1000 m depth, the core pattern was expressed by the 2.75° and 3.0°C isotherms. At Lat. 55°N, the 3.0°C isotherm formed a relatively warm tongue that extended southwest to include U of W Sta. 63. Further north the 3.0°C isotherm again curved, there to include U of W Sta. 6. POG Sta. 13 had the relatively high temperature of 3.25°C. At the eastern boundary of the region, from Dixon Entrance southward, temperatures higher than 3.25°C existed. The maximum observed temperature was 3.50°C, and was located about 50 miles southwest of Cape Flattery. The minimum observed temperature was 2.26°C, and was found

in the core area. Thus at 1000 m depth the observed range in temperature was appreciable.

The observed temperature range at 2000 m was much less than at 1000 m. The minimum was 1.80°C, and the maximum was 1.96°C. Lowest temperatures (less than 1.90°C) were found in a band delimited roughly by Lat. 51° and 54°N. A tongue of water of temperature less than 1.90°C extended northeast from Long. 148°W, running almost to the head of the Gulf of Alaska.

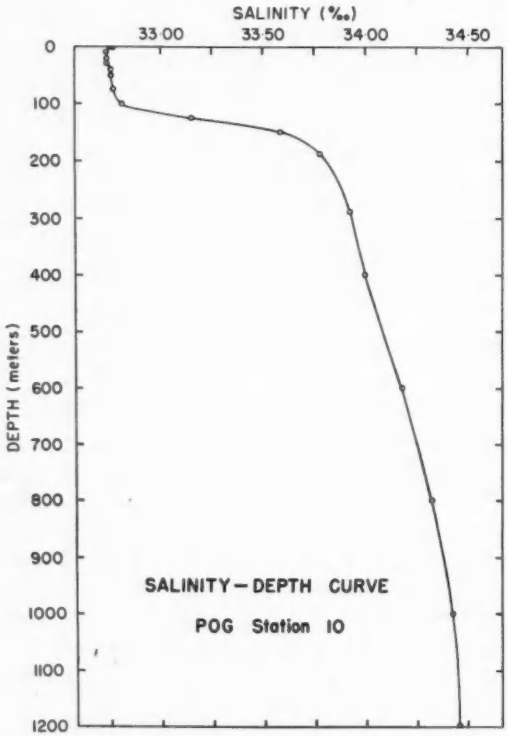

FIG. 11. Salinity–depth curve at POG Sta. 10.

THE SALINITY FIELD

CHARACTERISTICS OF THE VERTICAL DISTRIBUTION OF SALINITY. A typical example of the distribution of salinity with depth is illustrated in Fig. 11. The curve exhibits an essentially isohaline surface layer, an intermediate zone in which

salinity increases rapidly with depth (halocline), and a bottom or lower zone in which salinity increases gradually with depth.

In what follows, the characteristics of the halocline zone are discussed in some detail. It should be noted that in such an analysis of vertical salinity structure there is nothing to supplement the data given by the serial observations, i.e., there is nothing which corresponds to a bathythermogram. For this reason a very detailed discussion of the salinity structure of a water column cannot be given.

The depth of the top of the halocline (or of the bottom of the surface zone) varied from 55 to 140 m with the mean of 95 m. However, the variability in depth had no geographical significance but was quite random, such that large differences occurred between adjacent stations. This was not the case for the salinity at the top of the halocline. Figure 12 shows that this salinity was least at the coast and

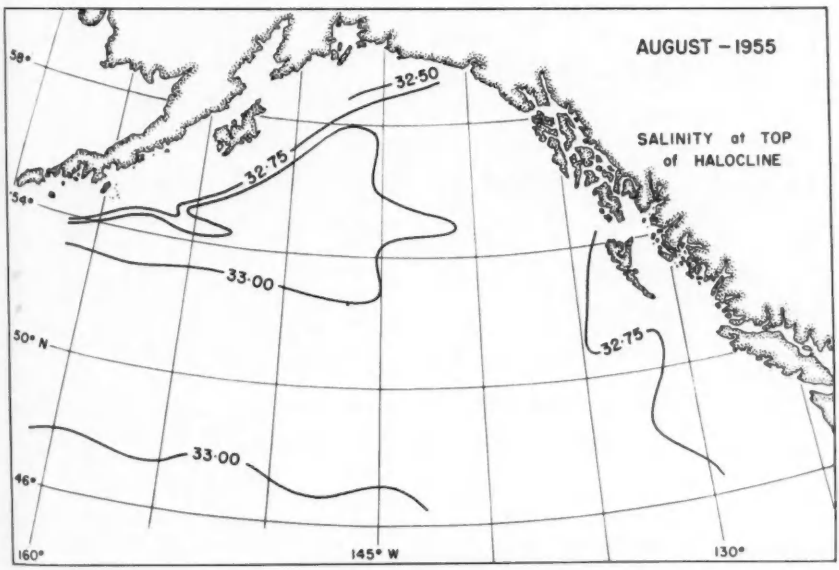

FIG. 12. Salinity at top of halocline.

was highest in the core area, and at the southwest limit of the region. The observed minimum and maximum values of this salinity are 32.47 and 33.20‰ respectively.

Tully (1957) found that the bottom of the halocline was indicated by the salinity 33.8±0.1‰. Thus the topography of the bottom of the halocline is obtained by contouring the 33.8‰ isohaline surface. This has been done in Fig. 13. Shoalest depths occurred in the core area, and off Cape Flattery. The minimum observed depth in the core area was 117 m. North of the core area the depth of this isohaline

surface increased quickly, exceeding 200 m just south of Kodiak Island. Southeast of the core area a slight declivity of the isohaline surface occurred, with depth exceeding 200 m in a band which ran approximately southwest from the Queen Charlotte Islands. Within the band, depths exceeded 225 m in two small areas and at POG Sta. 13 the salinity 33.8‰ was at 288 m. East of the band of maximum depth, the depth of this salinity decreased uniformly to 90 m, just off Cape Flattery.

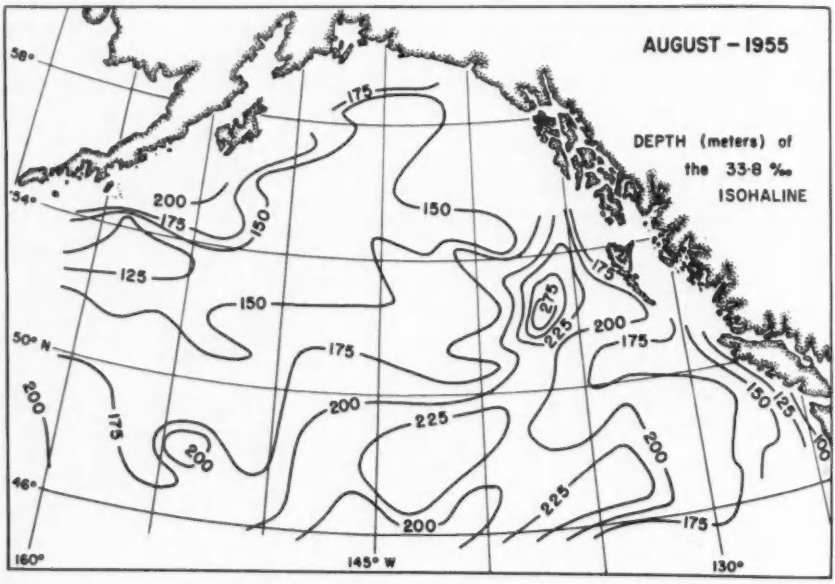

FIG. 13. Depth of the 33.8 °/₀₀ isohaline.

VERTICAL SECTIONS OF SALINITY. The salinity structure of the six vertical sections is illustrated in Fig. 14(A) through 14(F).

The halocline is readily discernible in all sections and is delimited by the isohalines 33.00 to 33.75‰ (33.80‰). The sections along Long. 161° and 147°W show that the halocline rose from the south, reaching shoalest depths in the core area, and descended near the continental shelf of the Alaska Peninsula. Near the Canadian coast the halocline rose.

Maximum surface salinity occurred in the center of the region and lowest salinity values were found near the coasts. Adjacent to the Alaska Peninsula, isohalines sloped down toward the coast, exhibiting a salt-wedge pattern. Near the Canadian coast the opposite was true. Here isohalines sloped upward toward the coast, so that a trough of low salinity water was formed off the coast. This structure is reported by Doe (1955).

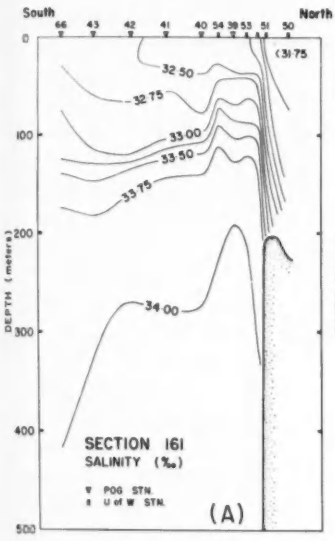

FIG. 14(A). Salinity — Section 161.

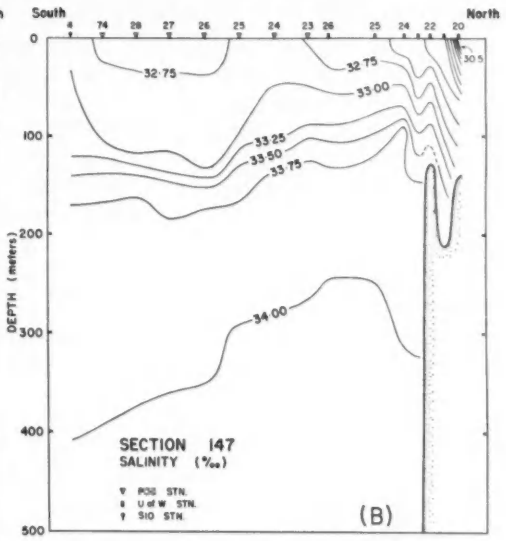

FIG. 14(B). Salinity — Section 147.

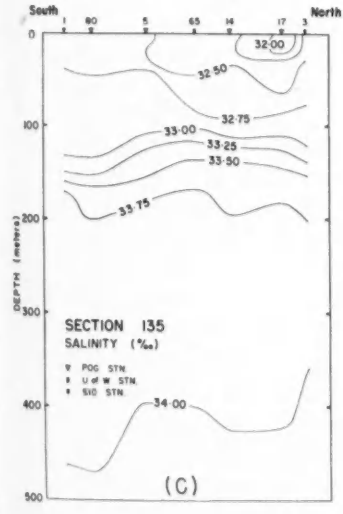

FIG. 14(C). Salinity — Section 135.

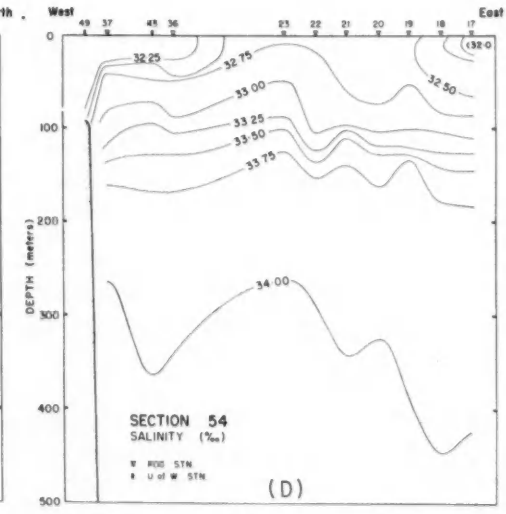

FIG. 14(D). Salinity — Section 54.

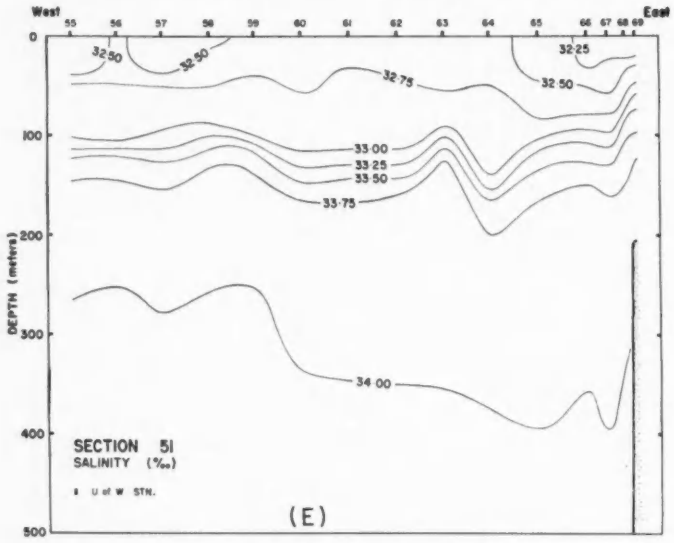

FIG. 14(E). Salinity — Section 51.

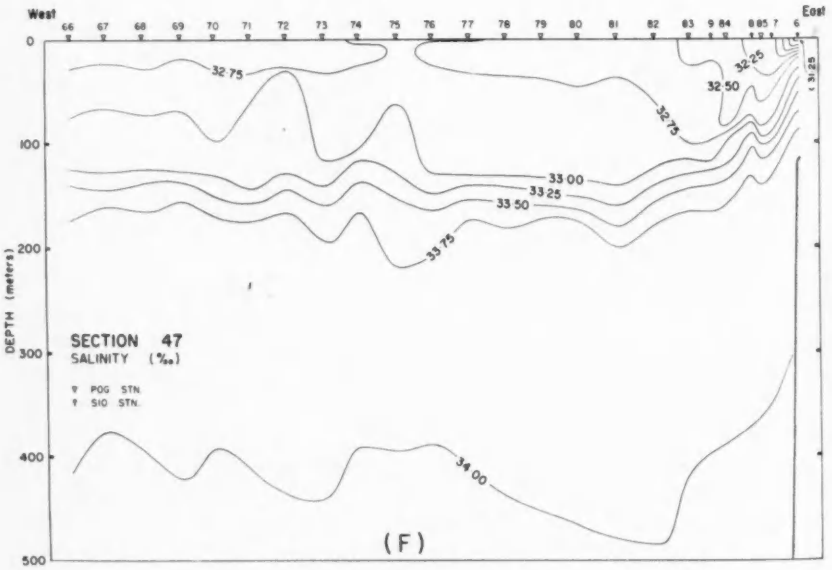

FIG. 14(F). Salinity — Section 47.

LATERAL DISTRIBUTIONS OF SALINITY. Figures 15(A) through 15(H) show the distribution of salinity at depths 10, 50, 200, 400, 600, 1000, and 2000 m.

At depth 10 m the maximum salinity values (greater than 32.75‰) occurred in the center of the region, while minimum values occurred at the coast. West, north, and east of the area of the maximum, the salinity decreased, but southward the salinity first decreased and then increased. At the southern limit of the region the essentially latitudinal isohaline of 32.75‰ intercepted the surface, and south of this the surface salinity continued to increase. The lowest observed value of salinity was 30.07‰ and was located in Shelikof Strait, between Kodiak Island and the Alaska Peninsula.

At 50 m depth the salinity was between 32.75 and 33.00‰ in half the region. Toward the coast lower values were found. Minima of less than 31.75‰ occurred in the vicinity of the Shumagin Islands and at the mouth of Cook Inlet. From the center of the region to the coast of Vancouver Island, salinity first decreased gradually to less than 32.50‰ and then increased quickly to greater than 33.00‰, the observed maximum of 33.18‰ occuring just off Cape Flattery. At the western edge of the region salinity values of less than 32.75‰ existed. As at 10 m, salinity increased southward. The 33.00‰ isohaline occurred on the western half of the southern limit of the region.

At 100 m depth the isohalines defined a large area of salinity between 32.75 and 33.00‰. This area extended as a band about 250 miles wide from the western limit to just over half way across the region, at which point the band spread north and south. South and east of this area salinity increased. Northwestward, the salinity first increased to the observed maximum of 33.77‰ about 140 miles east of Kodiak Island, then decreased toward the coast. The minimum observed salinity was 31.76‰ and occurred between the Shumagin Islands and the Alaska Peninsula. Isohalines north of the band area approximated the core pattern exhibited by the temperature isotherms.

Whereas at 100 m the observed difference between maximum and minimum salinities was 2.01‰, at 200 m this difference was 0.46‰. Most of the region had salinity between 33.80 and 34.00‰. Salinity was greater than 34.00‰ in a narrow tongue extending from the western edge of the region to Long. 150°W, along the axis of the core area. Minimum salinities (less than 33.80‰) were found in a tongue extending southwest from the Queen Charlotte Islands to the southern limit of the region, and in two small areas in the southeast part of the region. Adjacent to Vancouver Island and the Washington coast, salinity values were greater than 33.90‰. This was a secondary maximum.

At 400 m and at all greater depths to 2000 m the lateral salinity distribution had the typical core pattern exhibited by the corresponding temperature distributions. Maximum salinities were found in the northwestern part of the region.

Though at 1000 m the observed range in salinity was only 34.31 to 34.44‰, that at 2000 m was even less, i.e., 34.57 to 34.65‰. In spite of the small range, the core pattern was evident at 2000 m. Highest salinities occurred at the southeastern corner of the region.

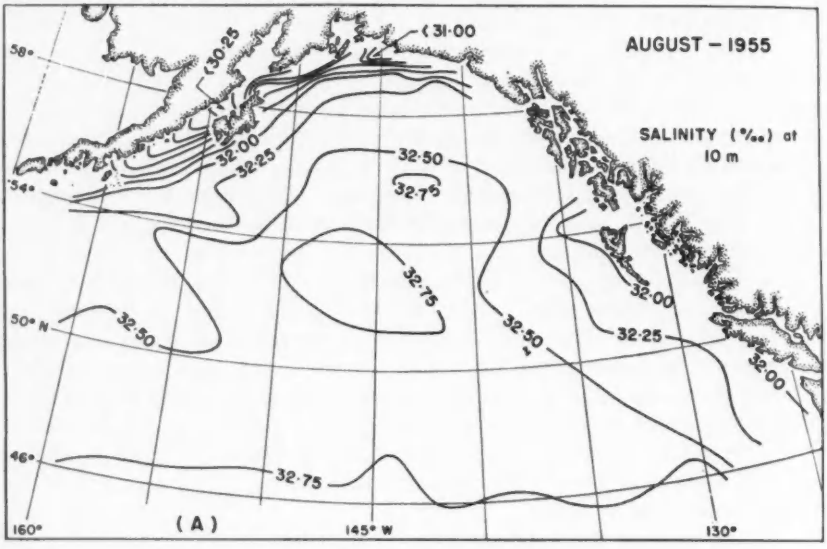

FIG. 15(A). Salinity at 10 m depth.

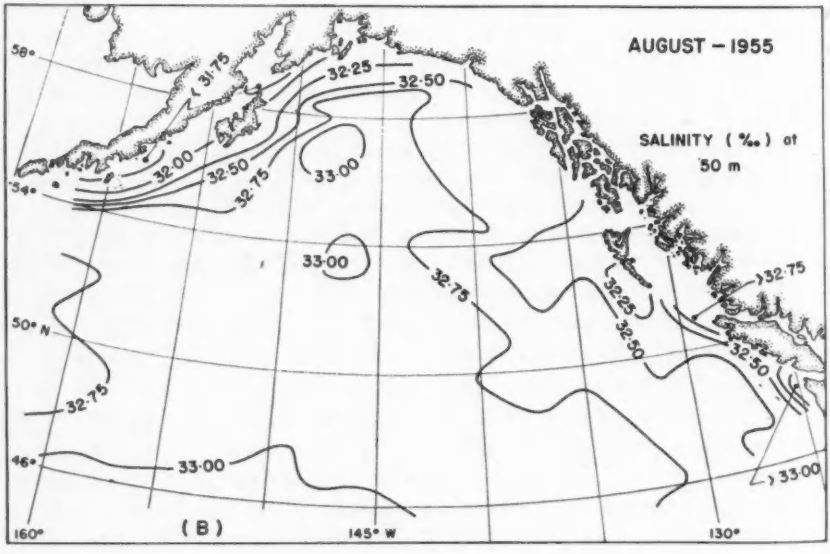

FIG. 15(B). Salinity at 50 m depth.

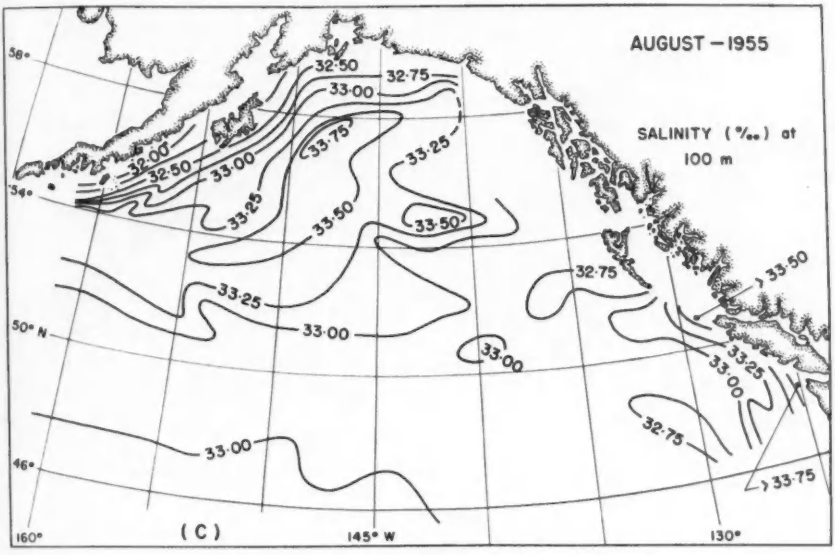

FIG. 15(C). Salinity at 100 m depth.

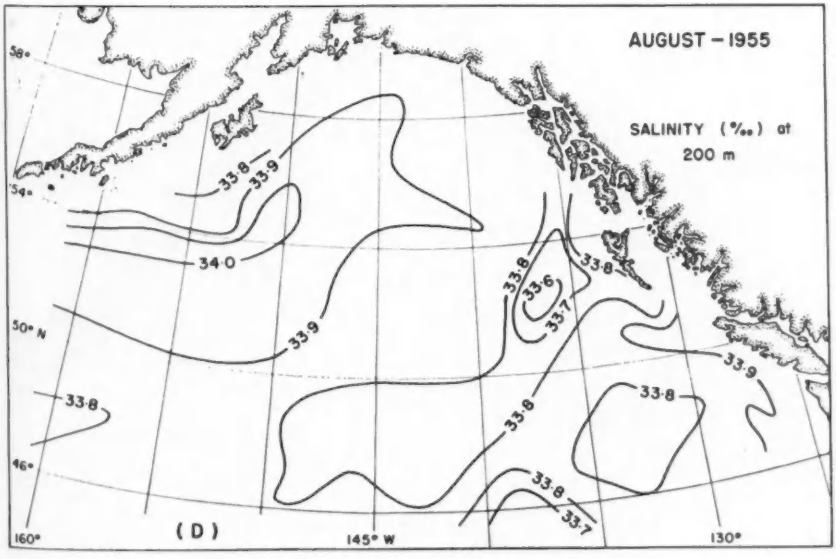

FIG. 15(D). Salinity at 200 m depth.

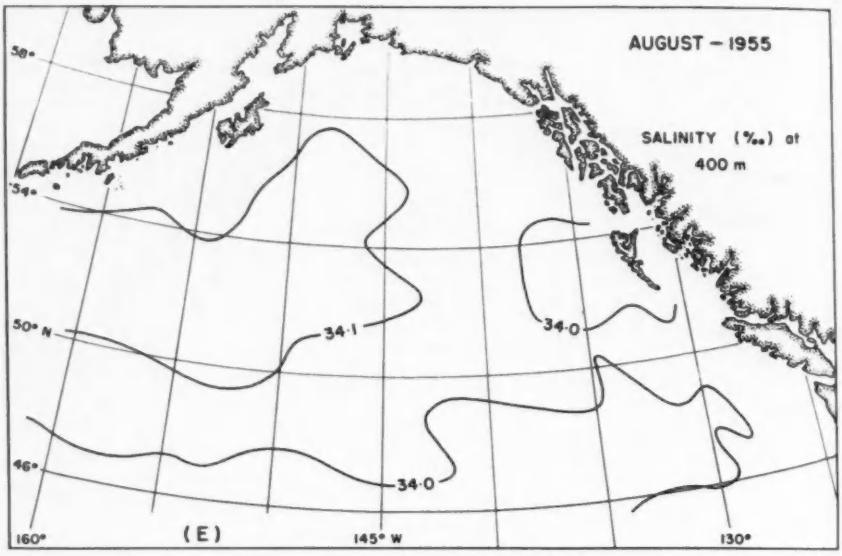

FIG. 15(E). Salinity at 400 m depth.

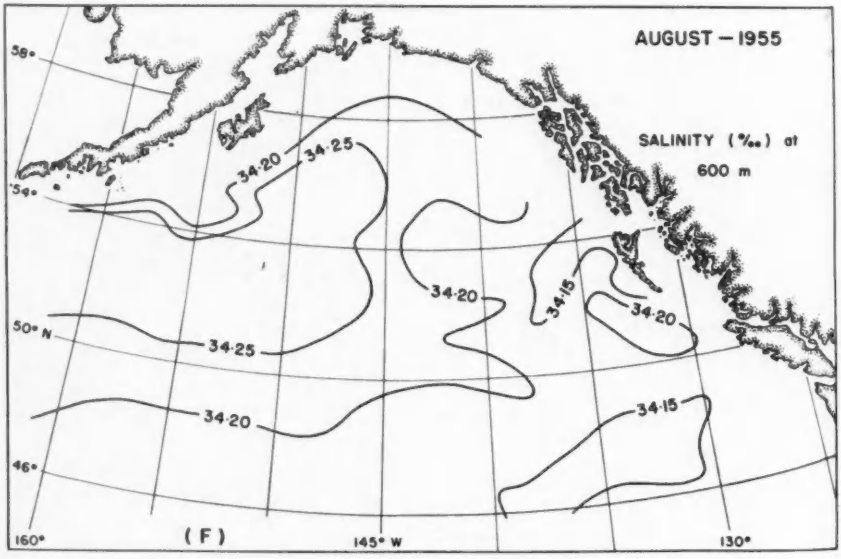

FIG. 15(F). Salinity at 600 m depth.

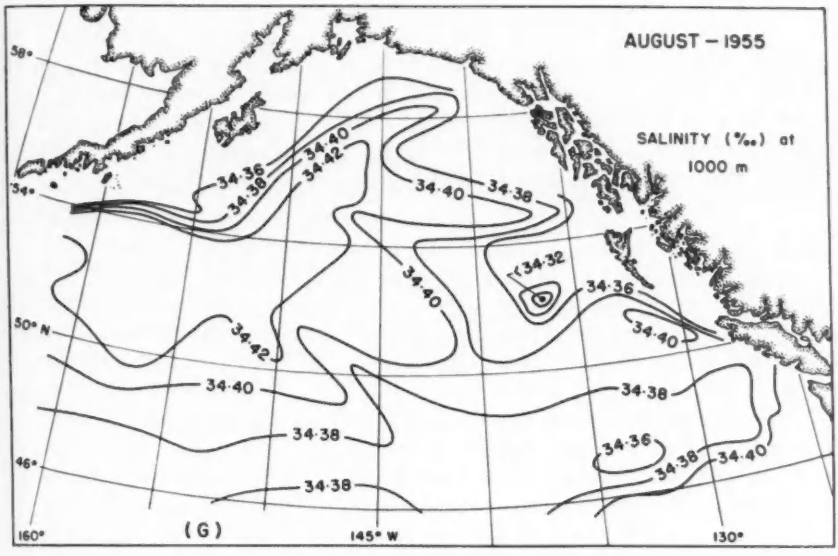

FIG. 15(G). Salinity at 1000 m depth.

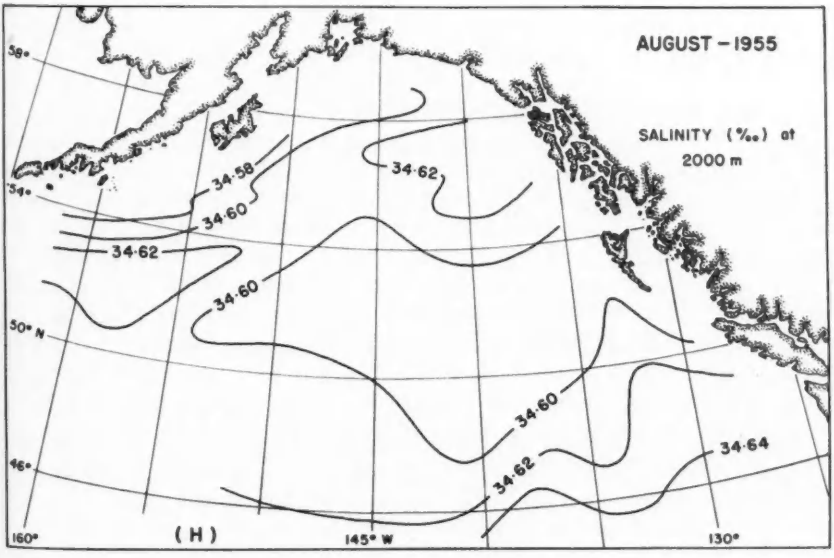

FIG. 15(H). Salinity at 2000 m depth.

THE MASS FIELD

CHARACTERISTICS OF THE VERTICAL DENSITY ANOMALY STRUCTURE. An example, typical of the distribution with depth of density anomaly (σ_t)[4, 5] is shown in Fig. 16. From the surface down, the curve exhibits: a shallow surface layer in which σ_t is constant; a shallow zone in which it increases rapidly; a zone in which it increases slowly; another but thicker zone in which it increases quickly; a lower zone which is characterized by a gradual increase with depth.

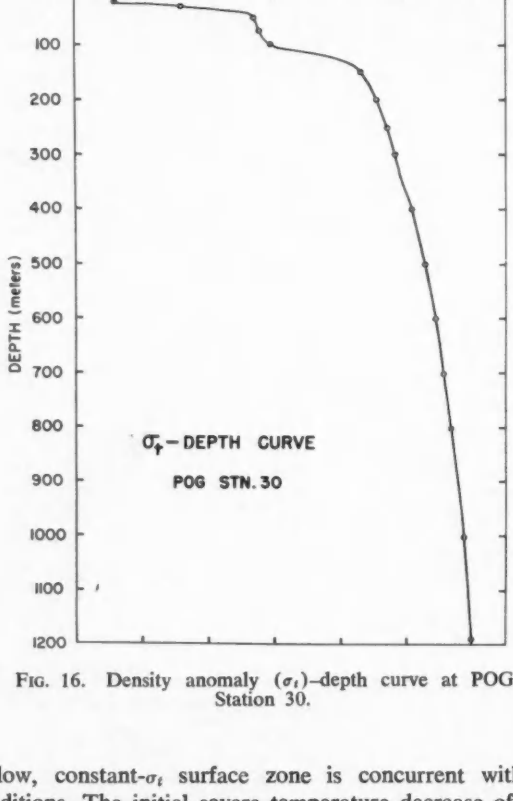

FIG. 16. Density anomaly (σ_t)–depth curve at POG Station 30.

The shallow, constant-σ_t surface zone is concurrent with isohaline and isothermal conditions. The initial severe temperature decrease of the thermocline induces the shallow layer of strong density anomaly gradient. This is termed the "temperature-dependent pycnocline". Small temperature variations and near-

[4] $\sigma_t = 10^3 \times (\text{density}_{s,t,0} - 1)$ expressed as milligrams per cubic centimeter.
[5] Throughout this report "density anomaly" is used interchangeably with σ_t and is not "density anomaly *in situ*."

isohaline conditions account for the intermediate zone of small density anomaly increase. The second zone of marked σ_t increase occurs within the halocline and so is termed the "salinity-dependent pycnocline". The weak density anomaly gradient in the lower zone is the result of similar gradients of temperature and salinity.

VERTICAL SECTIONS OF DENSITY ANOMALY. The distribution of σ_t in the six selected vertical sections is shown in Fig. 17(A) to 17(F). In general each section shows the double pycnocline; the first occurred at the depth thermocline, and the second and less well-defined occurred in the halocline.

In the section along Long. 161°W, the double pycnocline structure is easily marked. Surface σ_t values were highest in mid-section. In general the σ_t isopleths rose slightly from the south end of the section and then dropped abruptly at the edge of the continental shelf. The salinity-dependent pycnocline rose about 25 m at a distance 100 miles south of the shelf edge and the double nature of the density structure was lost there.

In the section along Long. 147°W, the double pycnocline structure was not as well marked as in Sect. 161. Surface σ_t values increased from the south to a maximum at mid-section, then decreased northward, becoming very low (less than 23.25) at the northern coastal end. As in Sect. 161, surface-layer isopleths rose slightly from south to north until over the edge of the continental shelf. There isopleths dropped sharply. All deeper σ_t isopleths rose from the south, but descended in the vicinity of the continental shelf edge.

Again, in the section along Long. 135°W, the double pycnocline structure was not well marked, but it was present. The salinity-dependent pycnocline was essentially level along the section. The mean density of a water column was less than in Sect. 147. The vertical density structure was very much like that of the south end of Sect. 147.

Surface σ_t values exceeded 25.00 in the middle, and became less than 24.25 at the east end of the section along Lat. 54°N. West of mid-section, the surface values decreased to less than 24.50 at POG Sta. 36, and rose slightly to 24.75 at the west end. All σ_t isopleths which were continuous across Sect. 54 had a shoalest depth in mid-section and in general descended toward the east end. West of mid-section the isopleths descended until about 125 miles off the continental slope, then rose slightly to the slope.

In the section along Lat. 51°N, the surface σ_t values were less than 25.00 at the west end, greater than 25.00 close to mid-section, and became less than 24.25 at the east end, over the continental shelf at Queen Charlotte Sound. The temperature-dependent pycnocline contained the σ_t isopleths 25.25 to 25.50 throughout the section. It was sharply delimited on the west side of the section. Eastward, with the surface waters becoming less dense, lesser σ_t isopleths entered this pycnocline, and some of those which defined the pycnocline on the west diverged to form a smooth density anomaly gradient. The salinity-dependent pycnocline was defined throughout by the isopleths of 26.25 to 26.50, and was supported on the west by that of 26.75, and on the east by 26.00. In general then, the salinity-dependent pycnocline became weaker from west to east. This pycnocline

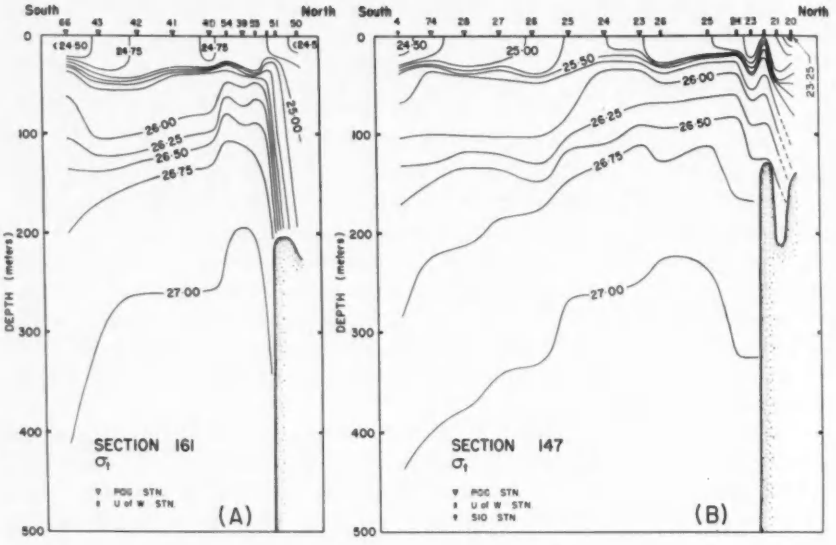

FIG. 17(A). Density anomaly (σ_t) — Section 161.

FIG. 17(B). Density anomaly (σ_t) — Section 147.

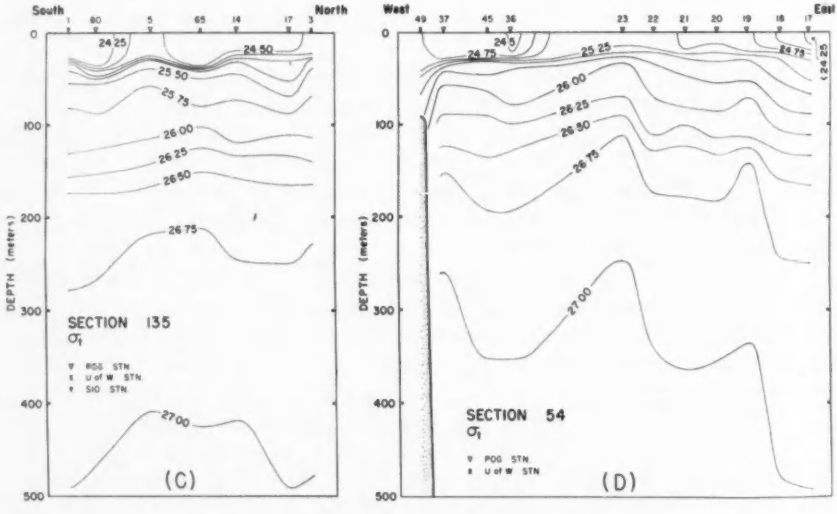

FIG. 17(C). Density anomaly (σ_t) — Section 135.

FIG. 17(D). Density anomaly (σ_t) — Section 54.

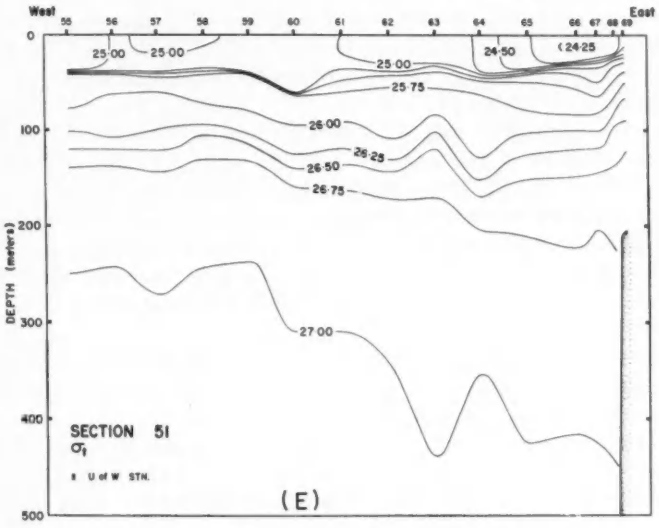

FIG. 17(E). Density anomaly (σ_t) — Section 51.

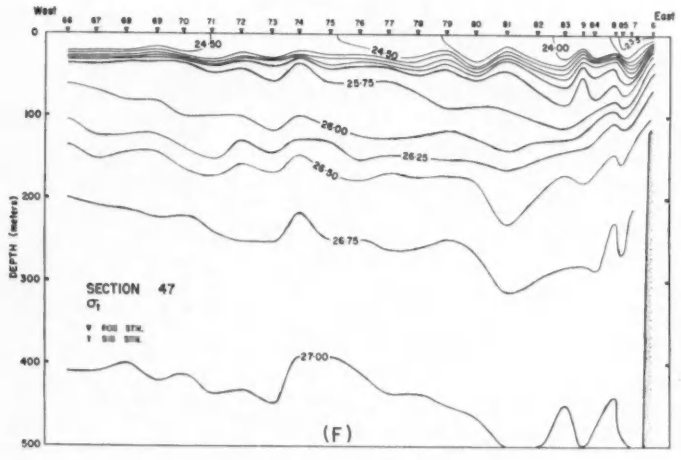

FIG. 17(F). Density anomaly (σ_t) — Section 47.

reached a maximum depth at U of W Sta. 64 (about 300 miles west of the continental shelf edge) and was 50 m shallower over the shelf edge. In contrast, the 26.75 isopleth descended about 50 m over the same distance, and all deeper isopleths in general descended from west to east. The rising of the halocline-dependent σ_t isopleths and the descent of deeper isopleths near the Canadian coast have been observed by Doe (1955).

The σ_t distribution in Sect. 47 was essentially the same as that of Sect. 51. Differences between the two sections were due mainly to the southern section being the warmer. Higher surface temperatures resulted in lower surface σ_t values and a well-delimited temperature-dependent pycnocline. σ_t isopleths from 26.00 to 26.75 again descended from west to east, reaching a maximum depth at POG Sta. 81, about 400 miles southwest of Cape Flattery. Eastward those isopleths rose sharply toward the coast. The 27.00 isopleth fell about 100 m in its traverse of the section.

LATERAL DISTRIBUTIONS OF DENSITY ANOMALY. Figures 18(A) through 18(G) show the lateral distribution of σ_t on those surfaces for which temperature and salinity were previously indicated.

The distribution at 10 m was characterized by maximum density anomaly in the center of the region – not in the core area. In all directions from the high density center, lower σ_t values were found. Southeast of the Kenai Peninsula a small area of secondary maximum density occurred.

At 50 m the center of maximum density was larger and was shifted northwest from the center of the region. Two other areas of similar maximum density

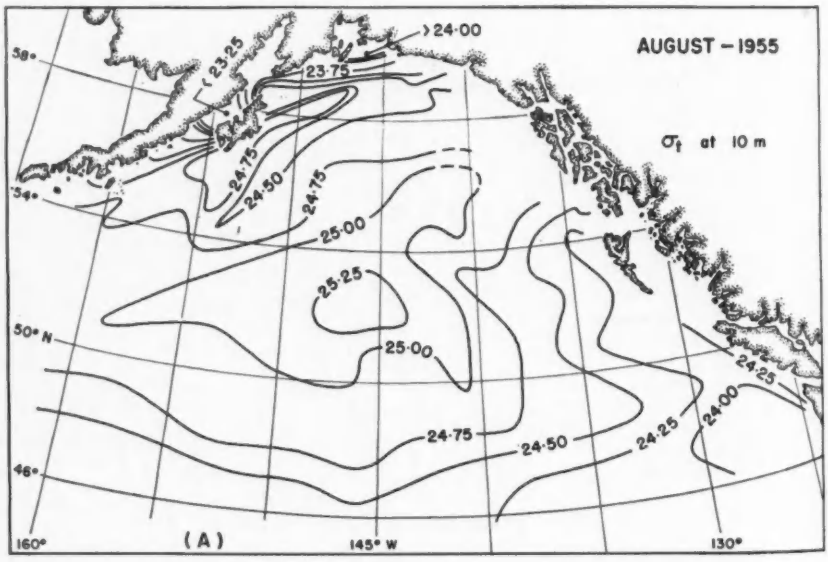

FIG. 18(A). Density anomaly (σ_t) at 10 m depth.

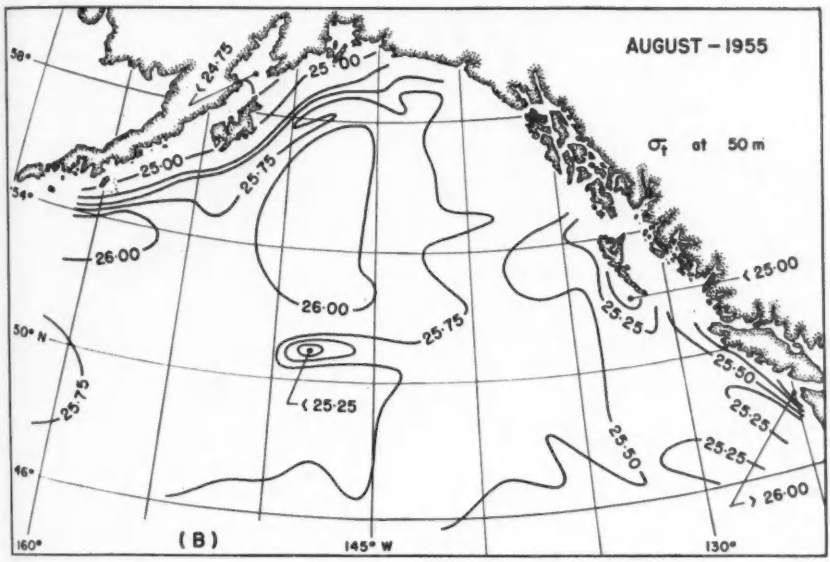

FIG. 18(B). Density anomaly (σ_t) at 50 m depth.

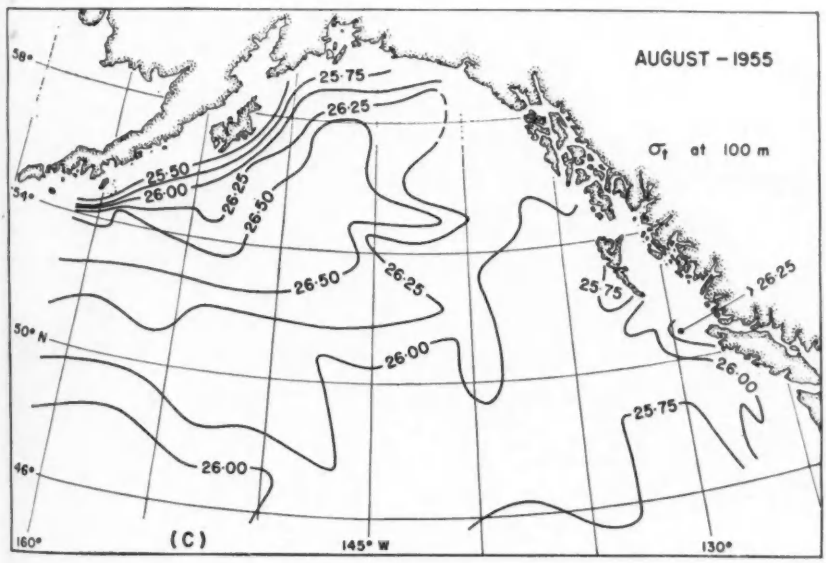

FIG. 18(C). Density anomaly (σ_t) at 100 m depth.

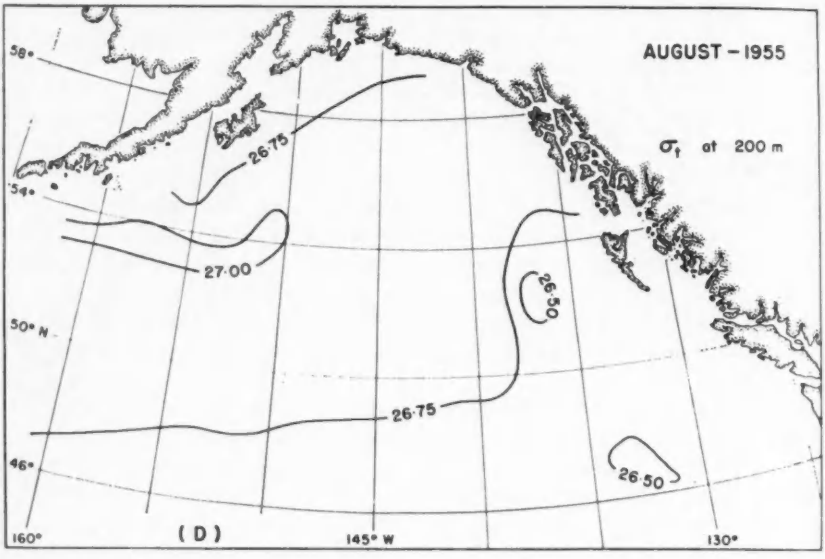

FIG. 18(D). Density anomaly (σ_t) at 200 m depth.

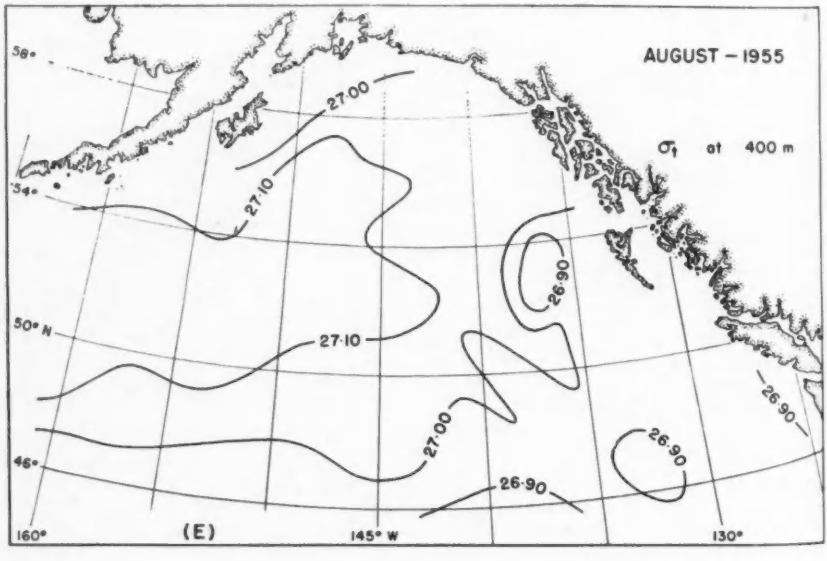

FIG. 18(E). Density anomaly (σ_t) at 400 m depth.

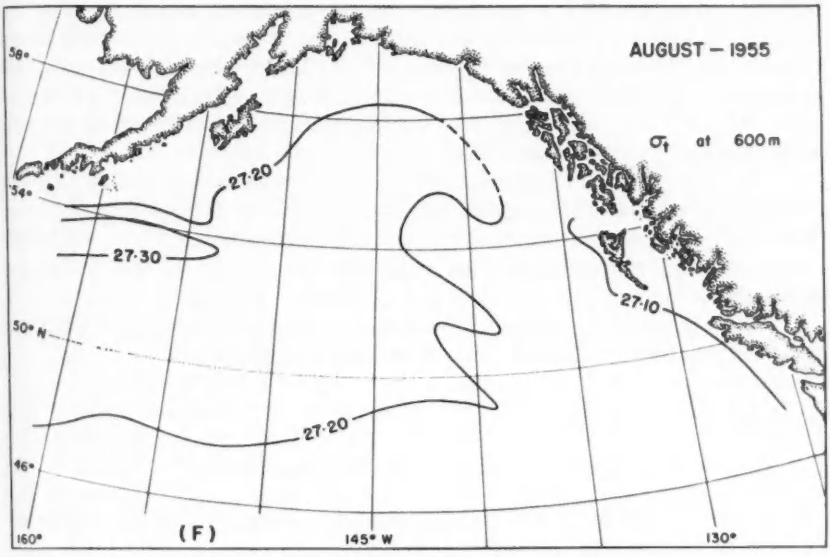

FIG. 18(F). Density anomaly (σ_t) at 600 m depth.

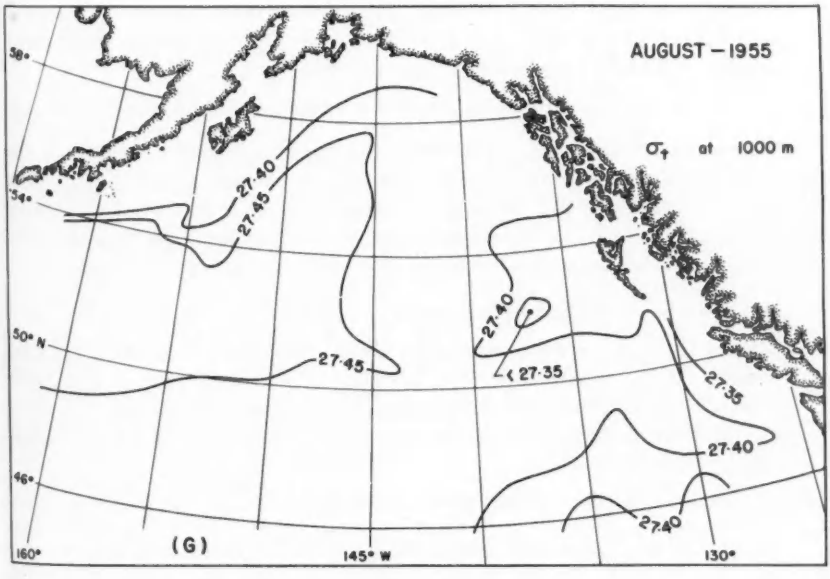

FIG. 18(G). Density anomaly (σ_t) at 1000 m depth.

occurred; one extended as a tongue into the west side of the region, the other lay off Cape Flattery. The latter concurs with the vertical Sect. 47. Northwest of the center of maximum σ_t a marked gradient existed. South of the high density center there was a small area of relative low σ_t. Two tongues of relatively low density water were at the southeast corner of the region, one of which imparted a strong gradient in the vicinity of Cape Flattery.

One hundred meters was the shoalest depth at which a lateral σ_t distribution exhibited the typical core pattern. From the core outwards, density anomaly decreased except for two areas which were relative maxima; one was on the southwest corner of the region and the other was off Vancouver Island and the Washington coast.

At 200 m and at all depths to 1000 m, the lateral density anomaly distributions had the core pattern, but lateral σ_t gradients decreased with depth.

Summary and Conclusions

The vertical structure of temperature was characterized by:

1. A surface isothermal layer of average depth 23 m which was presumably due to wind mixing.
2. A zone in which temperature decreased rapidly with depth (thermocline) to relative minimum temperature. The average temperature decrease was 6.9 C°.
3. A relative minimum temperature and the corresponding relative maximum temperature below it. The average difference between the two temperatures was 0.33 C°. Large differences (about 1 C°) and the absence of dichothermal structure are both considered non-characteristic.
4. A smooth temperature decrease with depth below the temperature maximum.

Below 100 m depth the lowest temperatures at any level were in the northwestern part, or core area, of the region. There was a strong temperature gradient between the core area and Alaska Peninsula and similar but weaker gradients east and south of the core. Maximum temperatures occurred off Cape Flattery.

The vertical structure of salinity was characterized by:

1. An essentially isohaline surface zone.
2. A zone in which salinity increased rapidly with depth (halocline) until the salinity 33.8‰ was reached. The halocline was essentially horizontal in the offshore region but it was slightly domed in the core area. In the vicinity of the continental shelf the halocline rose off the Canadian coast and descended off the Alaska Peninsula.
3. A lower zone in which salinity increased slowly and evenly with depth.

At 200 m and deeper, the lateral distributions of salinity exhibited the core pattern, with highest salinities in the core area. As for the temperature field, strongest salinity gradients occurred northwest of the core area.

The vertical structure of density anomaly (σ_t) was characterized by two pycnoclines. The shallower and sharper density anomaly increase was related to the thermocline and was denoted the temperature-dependent pycnocline. The other deeper and weaker pycnocline was associated with the halocline and is termed the salinity-dependent pycnocline.

Below 200 m depth the computed σ_t lateral distributions were, of course, the same core pattern distributions as salinity and temperature.

The existence of the dichothermal structure and of the halocline suggests a surface influence on structure. The influence extends below 100 m but in general not below 200 m. Therefore the bottom of the halocline is a good approximation of the bottom of the ocean troposphere. In turn, 200 m is a good approximation of the bottom of the halocline.

The six vertical sections suggest that below the limiting depth of the surface zone (i.e., below 200 m) the shape of any surface of constant property must be that of a skewed dome. This is verified by Fig. 19, 20 and 21 which illustrate the topography of the 4°C isothermal surface, the 34.0‰ isohaline surface, and the 27.25 σ_t surface. In each case the shoalest depth of a surface was in the core area. Away from the core area the depth of these surfaces increased, but the declivity of each surface was greatest north of the core area. Maximum depths of the surfaces were found adjacent to the Canadian coast except in the case of the salinity surface, which was deepest about 300 miles west of Cape Flattery.

It is to be noted that the observed range in depth of the 34.0‰ isohaline surface (190 to 485 m) fell well within that of the 4°C isothermal surface (55

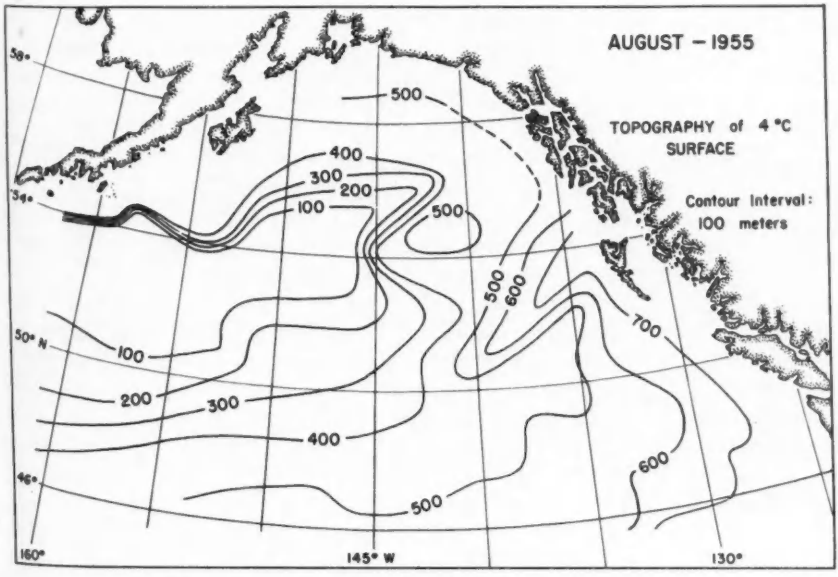

FIG. 19. Topography of the 4°C surface.

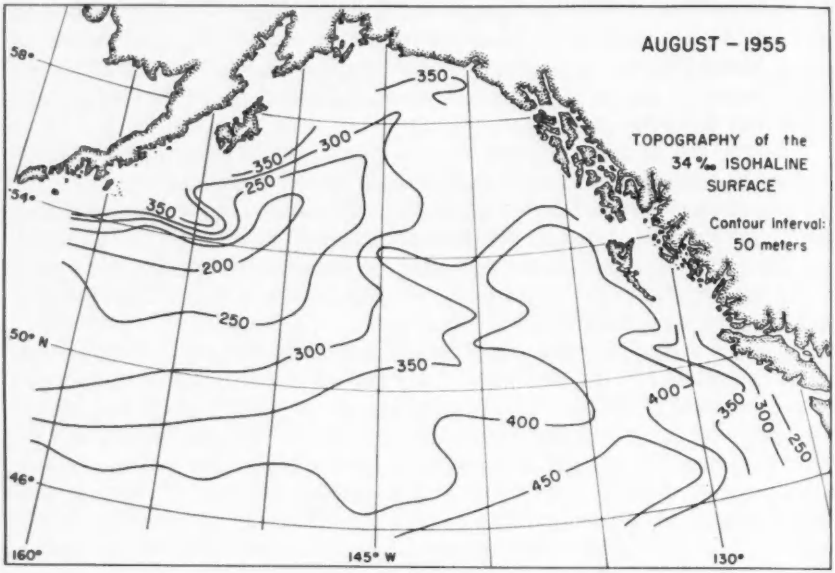

FIG. 20. Topography of the 34°/₀₀ isohaline surface.

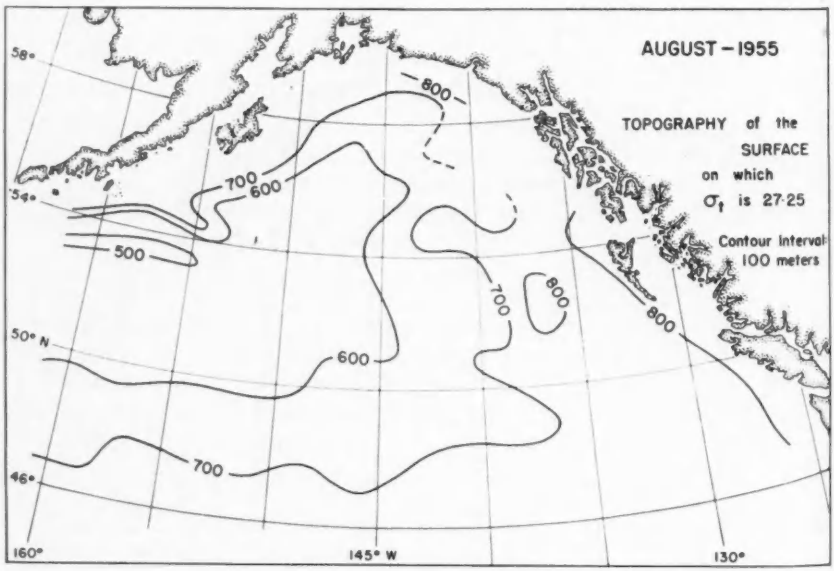

FIG. 21. Topography of the isopycnic surface on which σ_t is 27.25.

to 780 m). This indicates that the isohaline surface was flatter than the isothermal surface. Thus there were isotherm patterns on the σ_t surfaces with lowest temperatures in the core area.

From the "skewed dome" model, it is possible to envisage a circulation for the region. Current speed may be assumed approximately proportional to the inclination of the σ_t surfaces and current direction to be along contour lines with greater depths on the right of the current. Figure 21 suggests that there was a slow latitudinal movement eastward across the southwest part of the region. This veered north at mid-region to circulate around the Gulf of Alaska. The great inclination of the surfaces north of the core area indicates that there was an intense stream to the southwest along the Alaska Peninsula.

II. CURRENTS AND VOLUME TRANSPORT

In what follows, the presumed equipotential surface of geostrophic calculations is established at 2000 decibars (db). Next a new method is suggested for overcoming the difficulty presented by the extension of the level of no motion into the sea bottom. Then follows a discussion of the distribution with depth of current speed, stressing the influence of local surface wind. Examination of velocity profiles near 2000 db leads to the postulation of current at great depths, which is further investigated. Then the volume transport of water is discussed in relation to surface wind influence, intensification on the west side of the region and the effect of bottom topography.

METHOD

THE CHOICE OF THE EQUIPOTENTIAL SURFACE. Figure 22 illustrates the geopotential topography of the surface of the northeast Pacific Ocean referred to a presumed equipotential surface at 1000 db. The current is presumed to flow along the contours with velocity proportional to the gradient across them. The contours indicate that there was a slow latitudinal movement to the east, south of Lat. 50°N. East of Long. 145°W, the surface current turned north, ran to the head of the Gulf of Alaska and then turned southwest and underwent acceleration. The resulting strong current followed the Alaska Peninsula to Long. 165°W, and west of that it continued along the Aleutian Islands chain and was partially dissipated through the many passes into the Bering Sea.

In the past, the depth of motion for geostrophic calculations in this region has been chosen as 1000 db. However, it is noted in the present data that the pattern of isopleths of temperature and salinity (and hence of σ_t) at 1000 m (Fig. 10(G) and 15(G)) was similar to the contour pattern of dynamic height anomalies referred to a presumed equipotential surface of 1000 db. This implied the existence, at 1000 m, of a current in approximately the same direction as that indicated by the dynamic topography of the upper 1000 m. Therefore it is logical to presume a deeper equipotential surface.

The distributions of temperature and salinity at 2000 m are shown in Fig. 10(H) and 15(H), respectively. Comparisons with the data from 1000 m depth show that there was much less variation of properties, and presumably less geostrophic motion, at 2000 m than at 1000 m. Hence the 2000-db surface was chosen as the equipotential surface.

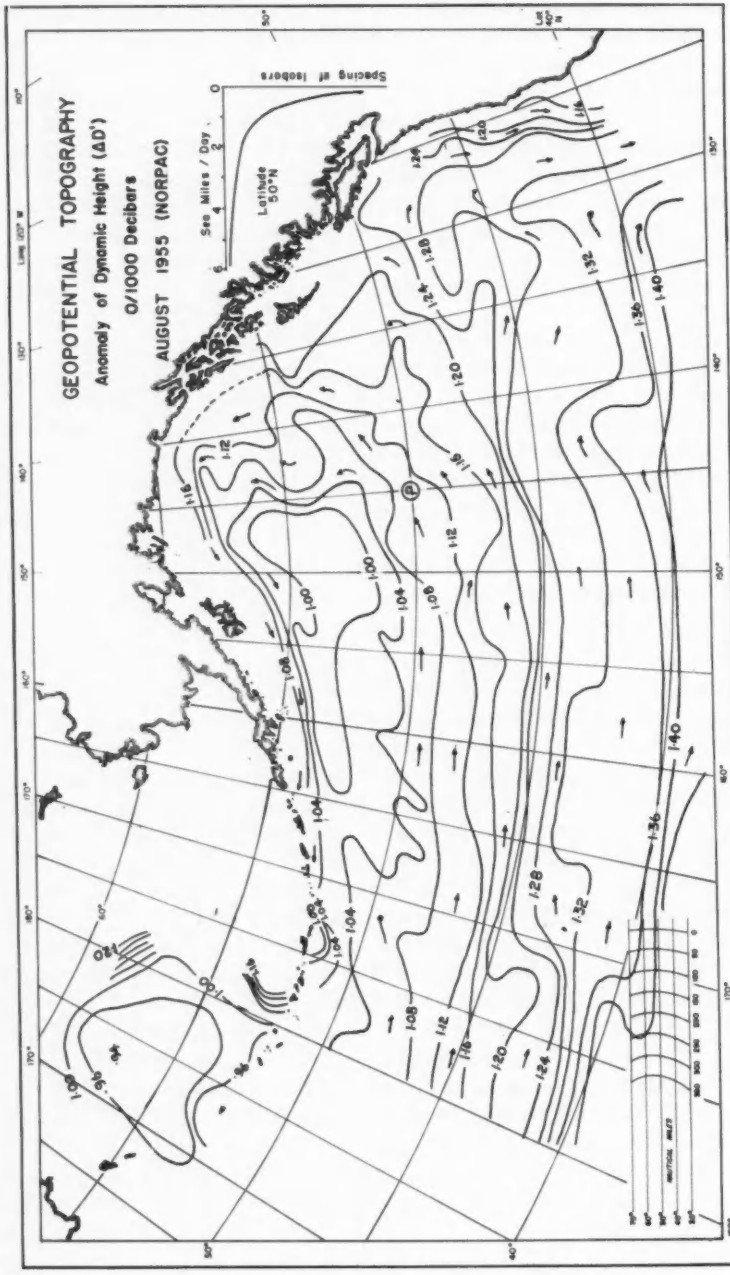

FIG. 22. Geopotential topography referred to 1000 decibars.

It is possible that below 2000 m a level exists at which there is less variation of properties. However, the present data are insufficient to define this, so the choice of the depth of the equipotential surface was limited to 2000 db.

The data in Table I are presented as an illustration of the consequences of using a 2000-db rather than a 1000-db reference level. A comparison of current

TABLE I. Surface current speeds and volume transports between U of W Sta. 29 and 30 for a 1000-db and a 2000-db equipotential surface.

	Equipotential level	
	1000–db	2000–db
Surface current (cm/sec)	9.0	13.3
Volume transport (10^6 m^3/sec)	2.78	6.50
Current at 1000 m (cm/sec)	0	4.3

speeds and volume transports for the two reference levels is shown, using U of W Sta. 29–30. When the equipotential surface was taken at 2000 db, rather than 1000 db, there was a current of 4.3 cm/sec at 1000 m between these two stations. This current was in the same direction as the surface current. The existence of this current at 1000 m made the surface current larger by a factor of 1.5. The greatest difference, however, occurred in volume transport. In this case volume transport was 2.3 times larger when referred to the lower level.

DYNAMIC HEIGHT ANOMALIES. The position of the stations used for dynamic calculations are shown in Fig. 23.

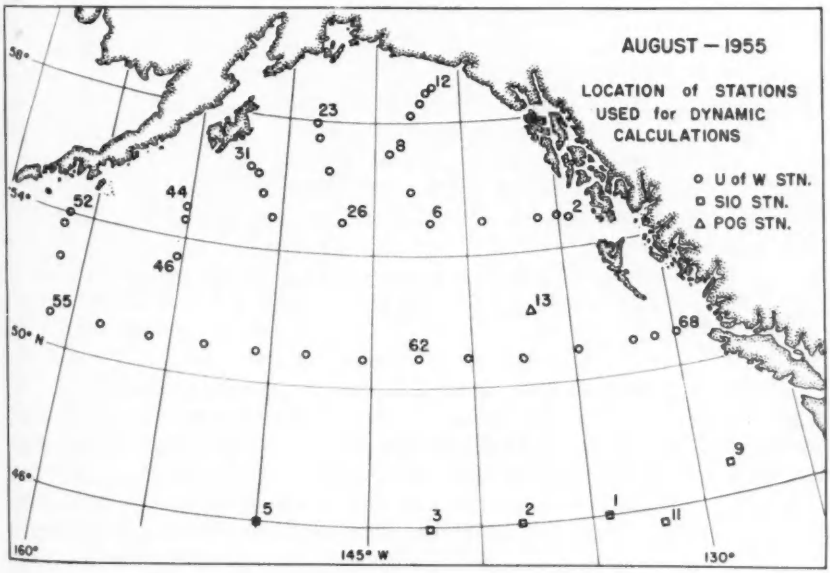

FIG. 23. Location of stations used for dynamic calculations.

FIG. 22. Geopotential topography referred to 1000 decibars.

The assumption of 2000 db as the depth of no motion precluded consideration of all POG stations and many U of W, and SIO stations, because of either shallow water or shallow sampling. Several U of W stations were sampled to about 1800 m yet not to 2000 m. For these, logarithmic extrapolations gave temperature and salinity values at 2000 m (Tully, 1957). Including these stations, it was possible to calculate dynamic heights referred to 2000 db for 36 U of W stations and 6 SIO stations, making a total of 42 stations within the region.

Shoreward of the 2000-m depth contour of the region there were 5 U of W stations located in water 1100 to 1500 m deep, which were sampled to about 950 m. These stations are numbers 2, 12, 23, 52, and 68. It was desirable to use these data for the dynamic assessment of the region, but the calculation of dynamic height referred to 2000 db at these peripheral stations implied the extension of the depth of no motion into the sea bottom below the stations.

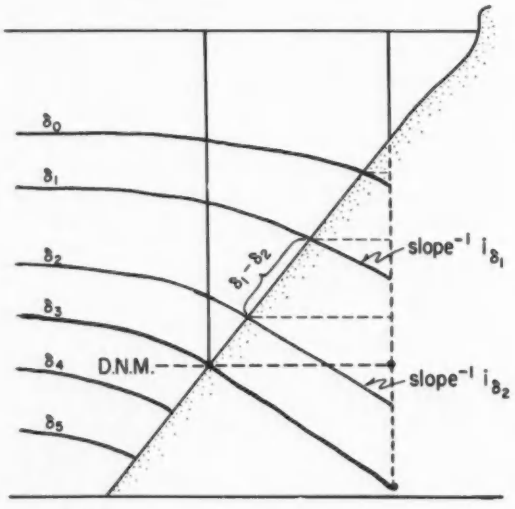

FIG. 24. Graphic methods for extension of depth of no motion (D.N.M.) into sea bottom.

Several methods are available to overcome the difficulty presented when the depth of no motion (D.N.M.) enters the bottom. Helland-Hansen (1934) introduced a method based on the assumption that along the bottom both the horizontal velocity and the slope of the isobaric surface vanish. In effect the curves of specific volume anomaly, δ [6], are continued horizontally through the bottom from the point of contact. In Fig. 24, this is represented by the horizontal broken

[6]Specific volume anomaly, $\delta = 10^5 \times$ (specific volume$_{s,t,p}$ – specific volume$_{35,0,p}$) expressed as cubic centimeters per gram.

lines. Jacobsen and Jensen (1926) proposed a similar method but with the additional assumptions that the sea bottom profile is a straight line and that δ curves are parallel and at equal distances. As another approximation, Sverdrup *et al.* (1942) suggest application of the equation

$$i_p = -\bar{i}_\delta(\delta_1-\delta_2)$$

where i_p = slope of isobaric surface

$\bar{i}_\delta$ = average slope of the surfaces δ_1 and δ_2 where they run into the bottom

$(\delta_1-\delta_2)$ = the difference $\delta_1-\delta_2$ along the bottom.

This is illustrated in Fig. 24.

The above methods are, at best, only expedients. All imply knowledge of the slopes of the δ surfaces at the bottom. This can be approximated only through extrapolation of curves. The methods of Helland-Hansen and Sverdrup require knowledge of the form of the bottom profile between stations, while the Jacobsen and Jensen method ignores it. In addition, all the methods require a scaled drawing of the section from which the various slopes and values of δ surfaces may be read off. Each method may be considered as uncertain.

A new method is now presented. Although it may be no more certain, it possesses the advantage that it does not require a scaled drawing of the section or knowledge of the slopes of the δ, or isobaric surfaces. It is necessary to know only the δ values at the observed or standard depths of the shallow, or nearshore station, and at the reference depth at the closest offshore station. The δ values are plotted against the logarithm of depth. Figure 25 shows the resulting plot for the offshore U of W Sta. 53. It is a very regular and slightly curved line, at least below the limiting depth of the ocean troposphere (200 m). The plot for the neighboring near-shore U of W Sta. 52 is similar but lies below that of the seaward station. The slope of the near-shore station curve is somewhat less than that of the seaward station, particularly at 1000 m. The reduction in slope at the lowest observed depth of U of W Sta. 52 suggests that its structure must approach that of the offshore station at greater depth. This, together with the presumption of the 2000-db equipotential surface, allows completion of the near-shore station δ curve, with an interpolated smooth curve which approaches the offshore plot roughly asymptotically, meeting at 2000 m. From the new section of the curve, δ values may be interpolated and computation of dynamic height anomaly proceeds from there. It is stressed that the method may not be more certain than any other previously used, but it is as reasonable, and is easier to apply in practice.

From the original data, and extrapolations made in this manner, dynamic heights were calculated using the methods described in U.S.N. H.O. Publ. 614 (La Fond, 1951).

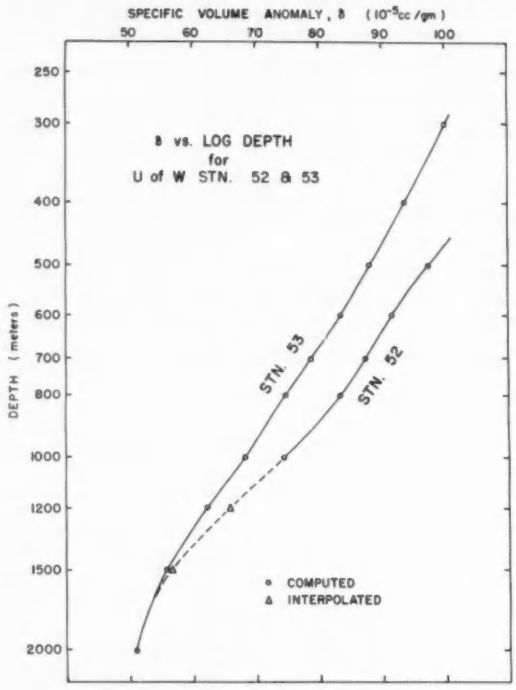

FIG. 25. Specific volume anomaly (δ) versus logarithm of depth — depth of no motion extension.

GEOSTROPHIC CURRENT AND VOLUME TRANSPORT. Profiles of mean relative current velocity versus depth were calculated using the formula of Helland-Hansen (1934) and assuming the theorem of circulation of Bjerknes *et al.* (1933):

$$u_z = \frac{10(\Delta D_A - \Delta D_B)_z}{L_{AB} 2\Omega \overline{\sin \Psi}};$$

where u_z = relative current at depth z m between Stations A and B;

$(\Delta D_A - \Delta D_B)_z$ = difference at depth z m between the dynamic height anomalies integrated between 2000 and z db for each station;

L_{AB} = distance in metres between stations;

Ω = angular velocity of rotation of the earth;

$\overline{\sin \Psi}$ = average value of the sines of the latitudes of the two stations.

A relative current-velocity sign convention is used. A positive current indicates flow with a southwest component; a negative current, a northeast component.

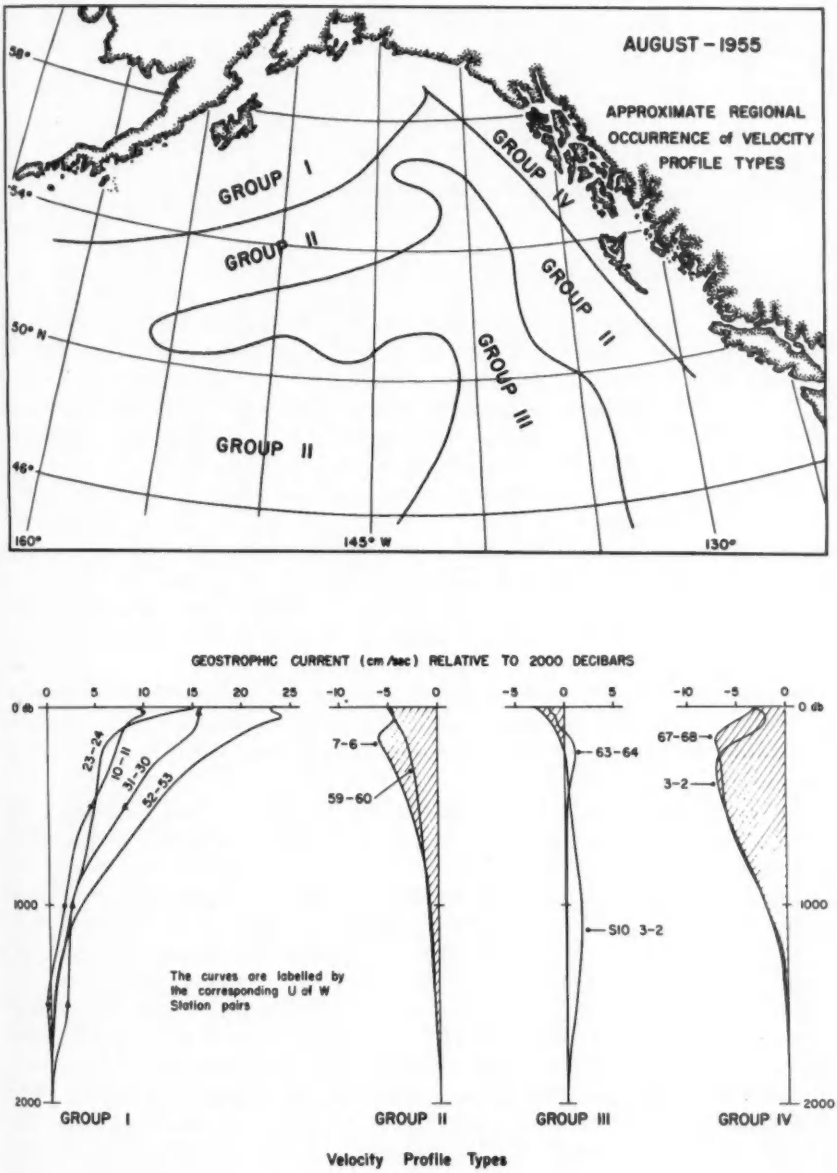

FIG. 26. Approximate regional occurrence of velocity profile types and profile types.

Geostrophic volume transport between stations is computed either through integration of the corresponding velocity–depth profile and multiplication by the distance separating stations, or from the equivalent expression

$$T_z = \frac{10}{2\Omega}\int_{-2000}^{z} \frac{[\Delta D_A - \Delta D_B]_z}{\sin \Psi}\,dz$$

where T_z = integrated volume transport between z and 2000 m.

Velocity Profiles

The distributions of mean relative current with depth between each pair of stations may be conveniently classified into four groups. The four groups and the regional occurrence of each are illustrated in Fig. 26.

Group I profiles occurred along the western side of the Gulf of Alaska. Current speeds were large and at all depths had a southwest or west component. Maximum current was at or near the surface and was as much as 24 cm/sec.

Group II are those current speed–depth profiles which at all depths had a northeast current component. Maximum speed was at the surface and did not exceed 5 cm/sec. Group II profiles occurred immediately seaward of Group I and Group IV profiles, and on the southwestern part of the region.

A surface layer current with a northeast component in contrast to the deeper current characterized the profiles of Group III. Current speeds were small at all depths. The upper current layer ranged in depth from 100 to 300 m.

Group IV profiles occurred adjacent to the Canadian coast. The relative current was directed northward at all depths. Here maximum velocity occurred at 200 to 400 m and was about 7 cm/sec. The surface current was about half the sub-surface maximum current.

INFLUENCE OF LOCAL WIND. The profiles of Groups III and IV indicate the effect of some surface acceleration such as wind. This leads to a consideration of the wind field over the Gulf of Alaska. Figure 27 shows the wind roses for the region for each 5-degree square of latitude and longitude. These data were taken from the Pilot Chart of the North Pacific Ocean for August 1956. The wind roses represent the average of all winds observed in the month of August for a period of about 100 years. As such, the Pilot Chart indicates the character of expected winds. It is readily seen that winds over the region are relatively weak and variable as compared with, say, the northeast winds that occur at Lat. 25°N. In other words, over the Gulf of Alaska no prevailing winds blow. However, it is possible to construct a vector resultant diagram using wind of constancy 40 to 60%. This is illustrated in Fig. 28. It is stressed that the Figure does not represent a distribution of prevailing wind, or a wind pattern, but it is an indication of vectors which exist about 50% of the time, but not necessarily concurrently. This wind tendency is essentially clockwise, except near the head of the Gulf of Alaska. There the wind becomes easterly, but constancy drops to about 20%. The strongest winds (greater than 10 miles per hour) occur in a tongue-like area extending

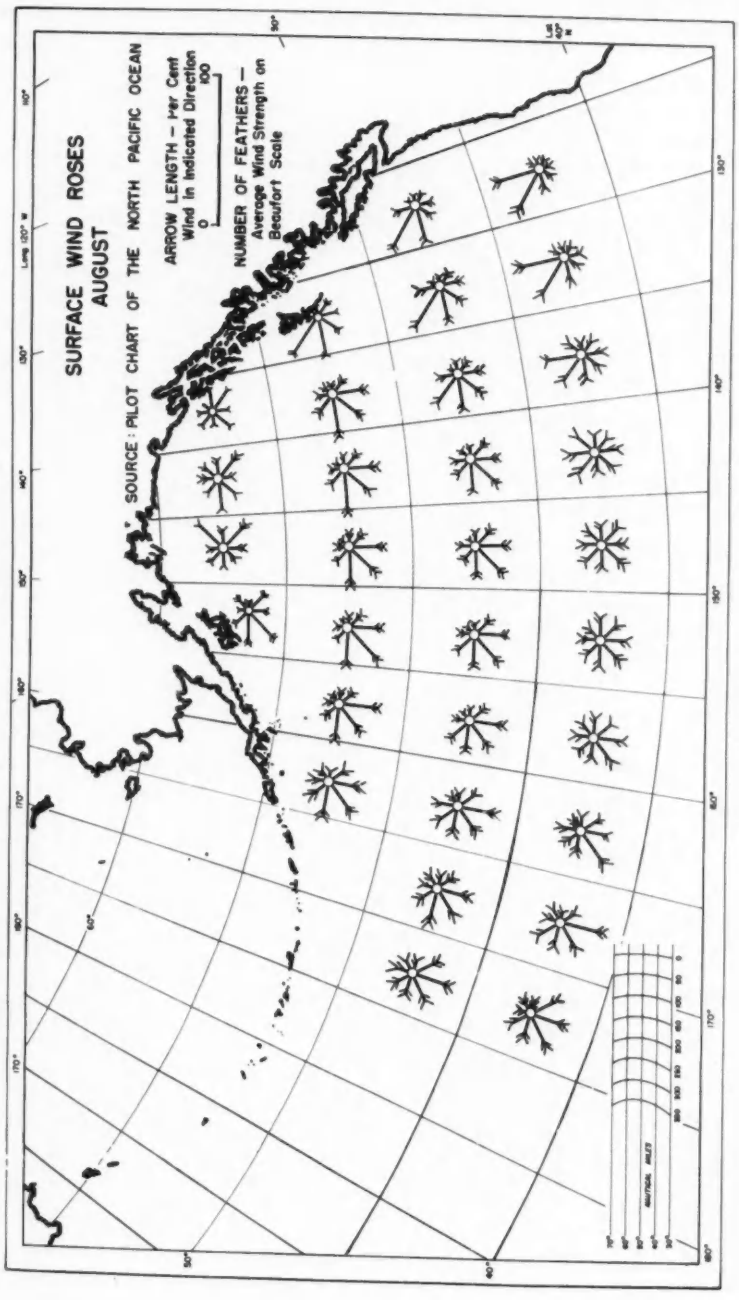
SURFACE WIND ROSES
AUGUST
SOURCE: PILOT CHART OF THE NORTH PACIFIC OCEAN
ARROW LENGTH — Per Cent Wind in Indicated Direction
100
0
NUMBER OF FEATHERS — Average Wind Strength on Beaufort Scale
NAUTICAL MILES

FIG. 27. Surface winds roses, August.

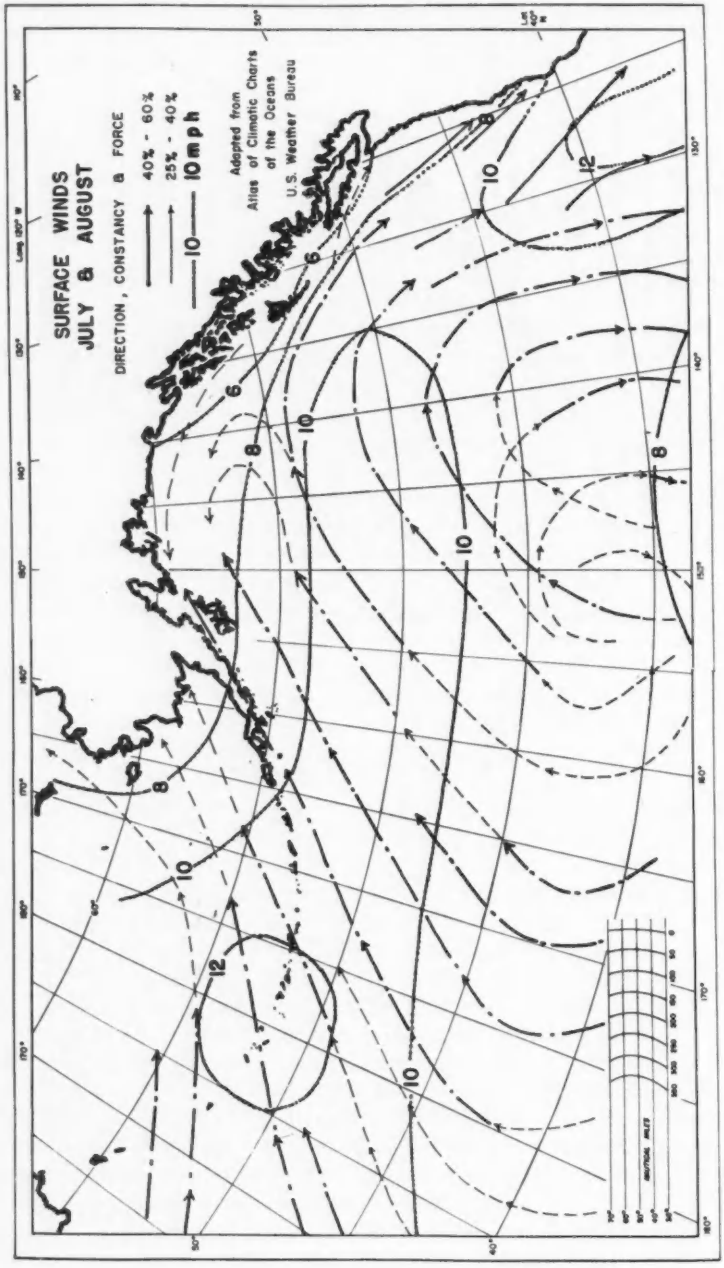

FIG. 28. Vector resultant wind field.

from the west side of the region east to Long. 135°W and from Lat. 48° to 53°N. North, east, and south of the tongue wind strength decreases.

In spite of the lack of a steady wind field over the Gulf of Alaska, there was an evident relation between the surface-layer current and the wind field as such. The most northerly of Group I current speed–depth curves (that of U of W Sta. 23–24) was located near the head of the Gulf of Alaska where the wind is weak and/or easterly. A strong surface current southwest existed. The most southwesterly profile of Group I (U of W Sta. 52–53) was in the area of strongest southwest wind. Here the southwest current was a maximum at 50 m, indicating surface retardation by the wind. Group II and III profiles were found in the central part of the region where the surface layer flow was in the same direction as the wind. Group IV profiles indicate northwest flow against a northwest wind and subsequent surface retardation. The flow indicated by Group IV curves has been observed on "Offshore" surveys (Doe, 1955).

In August 1955, the wind field, though not strong, influenced the upper-zone current profiles. However, the wind was not the only controlling feature since in some cases the current at all depths was directed opposite to the surface wind. It is concluded that in August 1955 the general current pattern in the Gulf of Alaska was not related everywhere to the local wind system.

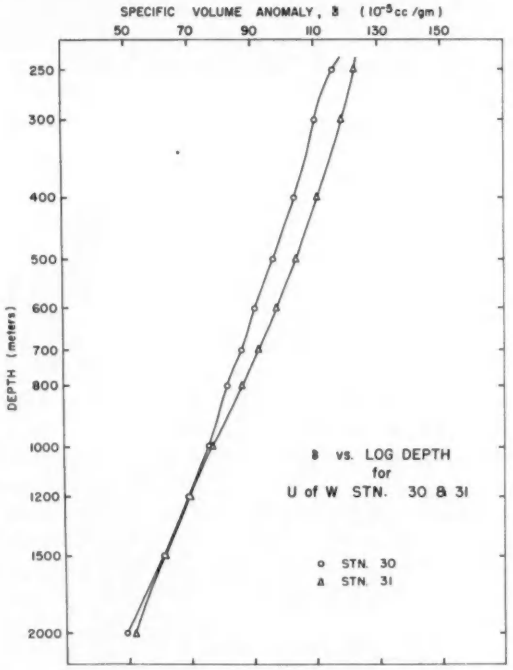

FIG. 29. Specific volume anomaly (δ) versus logarithm of depth at U of W Sta. 30 and 31.

Possibility of Abyssal Current

Since the curve of specific volume anomaly plotted against the logarithm of depth always is essentially linear (at least below 200 m) and since 2000 db was chosen as the equipotential surface, then the velocity and velocity gradient should go roughly asymptotically to zero at 2000 m. All current speed–depth profiles did reach zero at 2000 m, of course, because this was imposed on the data by the equipotential assumption. But in some cases there was a change in velocity gradient and a corresponding sharp drop in velocity near 2000 m. An example is the Group I profile of current between U of W Sta. 31–30 (Fig. 26). From 1000 to 1500 m the velocity decreased from 2.5 to 2.0 cm/sec, and in the next 500 m decreased to zero. Such a velocity–depth distribution is not impossible, but in this case it appeared that the imposition of the equipotential assumption had precluded current below 2000 m. If there is current at or below 2000 m, then the surfaces of the anomaly of specific volume, δ, will not be horizontal at that depth. In Fig. 29, the curves of δ versus the logarithm of depth for Sta. 30 and 31 are shown. The curve of Sta. 31 lies below that of Sta. 30, and the two are nearly coincident between 1200 and 1500 m. But below 1500 m the curves diverge, at least to 2000 m. Therefore the δ surfaces could not be horizontal in the vicinity of 2000 m.

It is now expedient to investigate the distribution with depth of δ surfaces near 2000 m. Figure 30 illustrates the δ field at that depth. Around the periphery of the Gulf of Alaska at 2000 m and in the center of the region, δ values were greater than 50 (for convenience, the factor-unit combination 10^{-5} cc/gram is

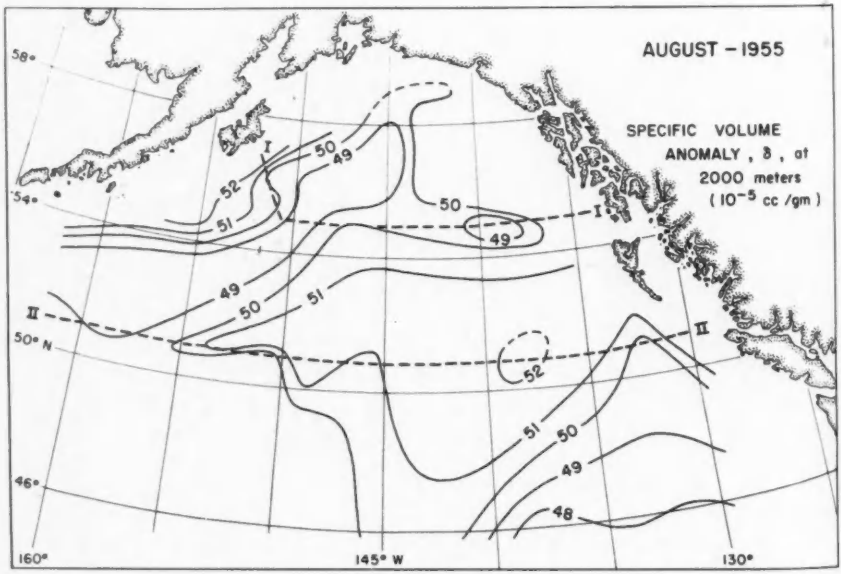

FIG. 30. Specific volume anomaly (δ) at 2000 m depth.

omitted), the maximum value observed being 52.5. The core area and the southwest and southeast corners of the region had δ values less than 50. A minimum observed value 48.2 was located in the core area, while in the southeast corner of the region there was a minimum of 47.4. It is apparent that in the vicinity of the core area the δ pattern at 2000 m was essentially the same as the surface current indicated by dynamic heights referred to 1000 db (cf. Fig. 22). Then if there was current at 2000 m (current which became zero at some greater depth) there would be circulation around the core area in the same direction as the indicated surface current.

The broken lines in Fig. 30 indicate where the vertical sections of Fig. 31 are located. Section I runs southwest from Kodiak Island to Lat. 55°N, and then

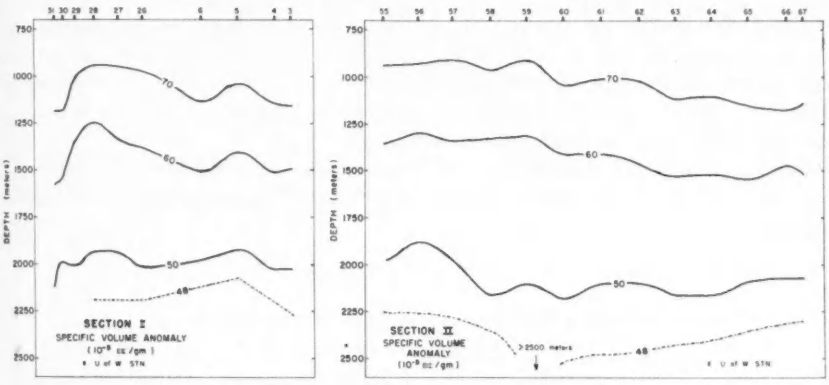

FIG. 31. Specific volume anomaly (δ) — Section I, Section II.

due east to Dixon Entrance. Section II is along Lat. 51°N, from Long. 161°W to the entrance to Queen Charlotte Sound. The sections show the distribution with depth of the specific volume anomaly, from 800 to 2400 m depth (where observations exceeded 2000 m).

In Sect. I, the δ isopleth 60 was at 1580 m at Sta. 31, 1250 m at Sta. 28, and 1500 m at Sta. 3. The isopleths of specific volume anomaly in the vicinity of 2000 m reflected, at least in part, the undulations of the 60 isopleth. The isopleths at 2000 m were not horizontal.

In Sect. II, the δ isopleths of value 70 and 60 descended from west to east. The 50 isopleth fell from 1880 m at Sta. 56 to 2160 m at Sta. 58. Over the eastern half of the section the 48 isopleth assumed a slope contrary to that of the 70 and 60 isopleths. Therefore, down as far as 2500 m, δ surfaces do not become and remain horizontal.

The slope of the 48 isopleth over the eastern half of Sect. II appears definite. If all deeper δ surfaces have the same slope, then there would be a southward current below a depth of no motion near 1000 m. It follows that, because data

from greater depths are lacking, no guess can be made of the direction of flow of the inferred abyssal current. Similarly, no guess can be made of the best equipotential surface, so its definition must remain as the level of least lateral gradients of properties, within the range of the data.

It is concluded that motion exists at least to 2000 m, and possibly below that level, but that the direction of abyssal current cannot be determined with the present data.

The assumption of no motion at 2000 m resulted in a mean northward current of 0.15 cm/sec at 1000 m in Sect. II. Though the current speed was small, the difference in transport induced by precluding motion between 1000 and 2000 m would have been 4.21×10^6 m^3/sec or about 44% of the transport relative to 2000 m. Suppose now that at 2000 m a mean current of only 0.05 cm/sec existed across the section, and that is was directed north, as is the surface current. If this current went linearly to zero at 2500 m (an arbitrary choice) then the assumption of zero motion at 2000 m would not account for a transport of 2.39×10^6 m^3/sec through Sect. II. Thus a current of 0.05 cm/sec at 2000 m with zero motion at 2500 m would make the volume transport 25% larger than through the same section with motion assumed zero at 2000 m.

This indicates the need for two things. First, observations should be made below 2000 m in the region. Second, observations of temperature and salinity should be as accurate as possible.

Volume Transport

The equation usually used to calculate volume transport is

$$T_z = \frac{10}{2\Omega \sin \Psi} \int_{-2000}^{z} [\Delta D_A - \Delta D_B]_z dZ$$

The equation is correct for latitudinal flow, i.e., true geostrophic flow. However, the flow considered here is not geostrophic, since the currents in the region are primarily longitudinal.

If it is assumed that absolute vorticity is conserved by the flow in the region, then the equation, slightly modified, may be used. The absolute vorticity of a water particle is

$$\xi_a = 2\Omega \sin \Psi + \xi$$

where $2\ \Omega \sin \Psi$ is the vorticity due to earth's rotation (Coriolis force) and ξ is the vorticity relative to the earth. Now when flow changes latitude there will be a change in Coriolis force. If absolute vorticity is conserved, there must be an equal and opposite change in relative vorticity. Therefore, introducing the term for relative vorticity in the transport equation,

$$T_z = \frac{10}{\text{constant}} \int_{-2000}^{z} (\Delta D_A - \Delta D_B) dz$$

The constant should be the sine of the latitude at which the relative vorticity is zero. Here the choice for the constant was the sine of the mean latitude of the

region, Lat. 53°N. With this, the greatest difference between a transport calculated assuming conservation of absolute vorticity and the corresponding geostrophic transport is about 10.5%.

The vector resultant of volume transport integrated over 2000 db for each station pair is shown in Fig. 32. Volume transport in the southeast corner of the

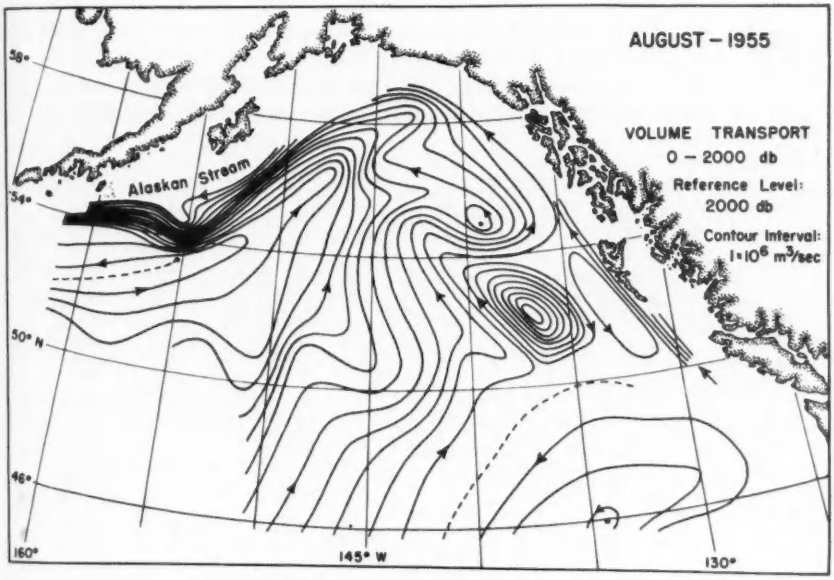

FIG. 32. Volume transport, 0 to 2000 decibars.

region was the upper half of a large anti-clockwise eddy of radius about 300 miles. Water flow in the eddy was about 3×10^6 m^3/sec. North of the anti-clockwise eddy was a smaller but more intense clockwise eddy whose flow was about 8.5×10^6 m^3/sec. Between this intense eddy and an apparent strong northward flowing current near the Queen Charlotte and Vancouver Islands lay a weak elongated anti-clockwise eddy. The northerly near-shore current comprised at least 3×10^6 m^3 of water per second. The term "at least" must be employed because observations did not extend to the coast. West of the eddies, or in the center of the region, the mean current flow was north to northeast. The boundary between this flow and the opposite flowing eddy of the southeast corner ran approximately west and then southwest from Vancouver Island. The broad northerly current in the center of the region had the magnitude of 14×10^6 m^3/sec. At Lat. 51°N, the flow curved to the right and then back again. A similar but more marked deviation occurred at Lat. 55°N. The deviation of the right half of the flow had the form of a "hairpin" curvature. A small cyclonic eddy was located in the eye of the "hairpin". As recovery from the sharp deviation occurred,

the near-shore current of the North American coast added to the transport and the whole continued northwest around the head of the Gulf of Alaska. West of Long. 145°W, the flow turned southwest and underwent acceleration with the result that marked intensification occurred. A stream 100 miles wide which passed at least 17.5×10^6 m^3 of water per second coursed southwest following the Alaska Peninsula. At Long. 155°W, the stream turned west and carried out of the region. This strong current may be called the *"Alaskan Stream."*

These may be compared to the Gulf Stream whose water transport is of the order of 75×10^6 m^3/sec (Sverdrup *et al.*, 1942).

INFLUENCE OF SURFACE WIND. A comparison of the 0- to 200-db volume transport pattern with that of the summer surface wind field (Fig. 28) shows

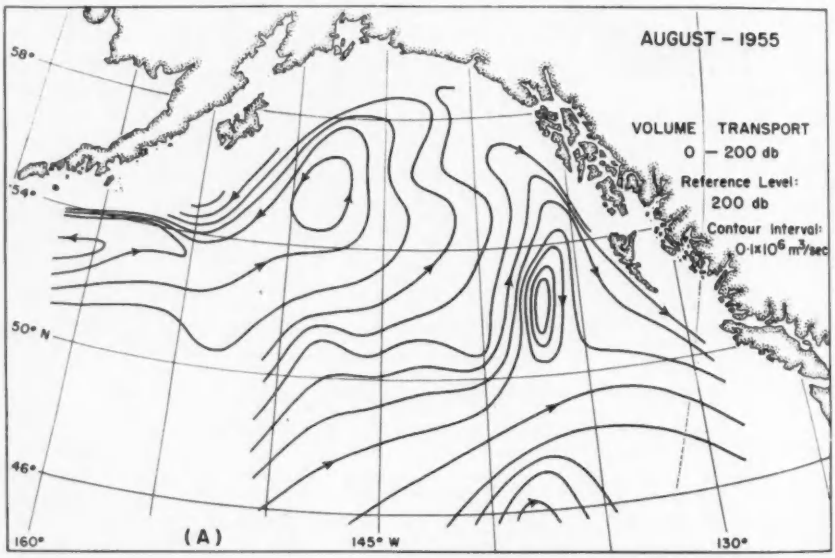

FIG. 33(A). Volume transport, 0 to 200 decibars, D.N.M. 200 decibars.

a marked difference. Over the large cyclonic eddy and near the Canadian coast the wind usually blows in directions opposite to that of the transport.

Since the limiting depth of surface influence was defined as 200 m, and since it was established that there was a wind effect on upper zone currents (page 615) then the 0- to 200-db volume transport, relative to 200 db, is the integral of surface wind influence.

The vector resultant of volume transport of the ocean troposphere, relative to 200 db, is shown in Fig. 33(A). Comparison with the surface wind distribution (Fig. 28) shows the almost complete correlation of wind-field and transport. Only adjacent to the Alaska Peninsula was the upper zone current, relative to 200 db,

directed up-wind. In this area only the near-surface 50 m of water was retarded (Fig. 26), and integration from 200 db masked that feature.

The most marked differences between the flow patterns of Fig. 32 and 33(A) are on the east side of the region. Off the Canadian coast, a southeast flow was indicated when the reference level is 200 db but the flow was northwest when referred to 2000 db. Over the southeast corner of the region the circulation was essentially clockwise for the shallow reference surface and anti-clockwise for the 2000 db equipotential surface.

It is stressed that the upper zone transport pattern of Fig. 33(A) is relative to 200 db and as such is not the "absolute" transport of the upper zone. Figure 33(B) shows the transport pattern of the same upper zone but referred to the

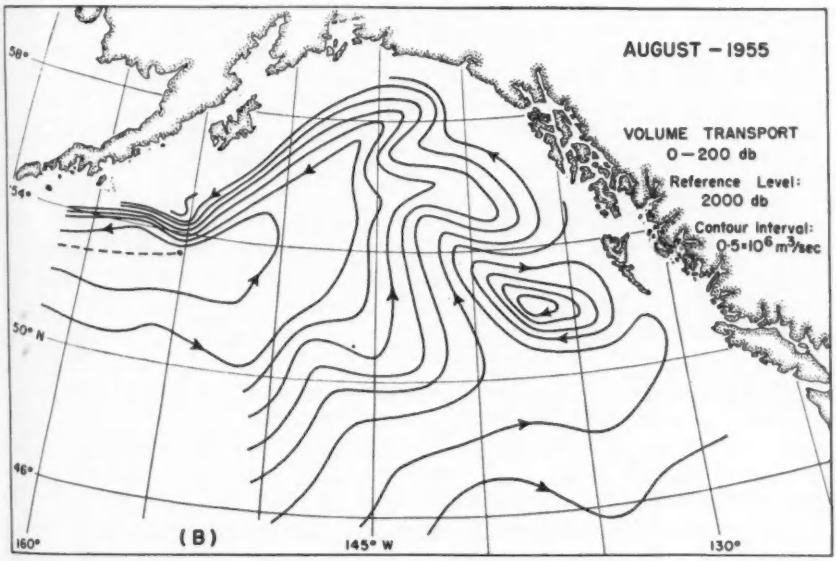

FIG. 33(B). Volume transport, 0 to 200 decibars, D.N.M. 2000 decibars.

2000 db surface. This flow pattern is the "absolute" circulation of the upper 200 m. The magnitude of the flow was about five times larger than that of the "relative" flow. Off the Canadian coast the flow indicated was northerly. Over the southeast corner of the region the current was essentially latitudinal.

COMPARISON WITH CONDITIONS IN AUGUST 1950. The intense anti-cyclonic eddy of Fig. 22, 33(A) and 33(B) was observed by Doe (1955) during August 1950. Figure 34 shows that at that time the eddy was centered about 100 miles southwest of its position in August 1955. Furthermore, in 1950, an elongated anti-clockwise eddy lay east of, and adjacent to the intense coastal eddy, and the near-shore current off the Queen Charlotte Islands was northerly. These last two

recurred in 1955 (Fig. 32). In the southern part of the region in 1950 the flow indicated was essentially latitudinal, except for the southeast corner where a cyclonic circulation existed. This is much like the flow pattern of Fig. 33(A). It is concluded that, within 600 miles of the Canadian coast, the circulation pattern which existed during August 1950 was similar to that of August 1955.

The eddy system was not present in August 1951. Therefore it appears that this feature is recurrent, but not necessarily perennial.

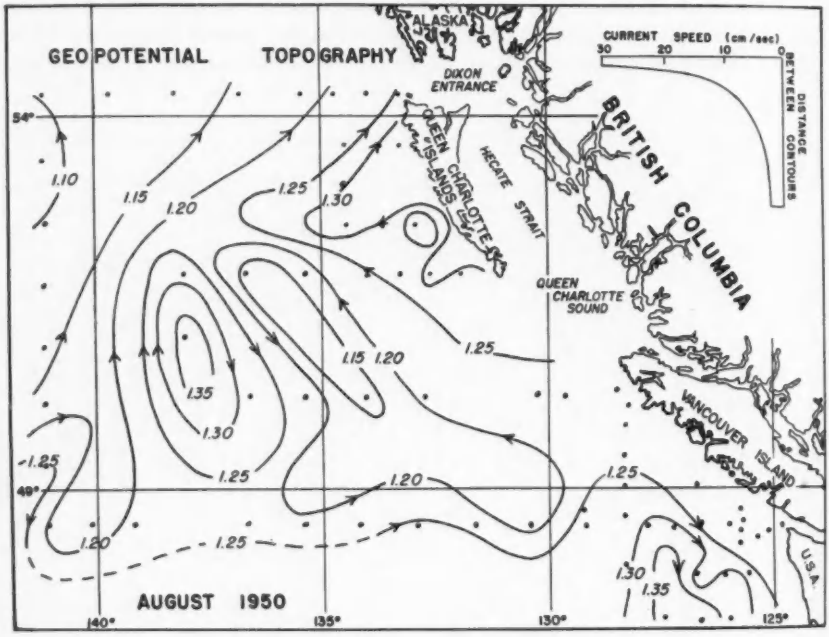

FIG. 34. Geopotential topography, August 1950 (Doe, 1955).

VERTICAL MOTION AT THE NULL FLOW LINE. At the boundary between the slow cyclonic eddy and the northerly current in mid-region (Fig. 32) it is expected that there should have been, somewhere in the water column, either or both of a convergence or divergence. From Fig. 33(B) it is known that the mean transport of water above 200 db was opposite to the flow of the cyclonic eddy, or in the same direction as the main surface flow in mid-region. Therefore, it is not expected that there was a divergent process at the sea surface along the indicated null line. This was borne out by the lateral distribution of properties at 10 m depth, for there were no discontinuities in the essentially latitudinal pattern across the boundary. The velocity profiles for the station pairs, in and around the eddy, showed that flow in the direction of the eddy began at roughly 175 m. Then if an operative divergent process existed, it should have been indicated either by the

lateral distribution of properties below 100 m, or by the topography of surfaces below that depth.

Superposition of the topography of the salinity 33.8‰ (Fig. 13) on the 0- to 2000-db volume transport pattern shows that along the null line of the flow, this salinity occurred at a relative minimum depth, never exceeding 205 m. In each side of the boundary, its depth exceeded 225 m and attained 245 m. Thus there was an apparent relation between the depth of the index salinity and the position of the null flow line.

The depth of the temperature minimum and maximum (Fig. 6(A) and 7(A)) also was a relative minimum along the null flow line. In addition, the dichothermal structure was absent in a small elongated area just north of this boundary.

These observations suggest that there was a slight uprising of water at the boundary and a corresponding slight sinking on each side. The process was internal, since it was not indicated at 100 m and shallower depth.

No estimate can be made of the depth to which the divergent process extends. There are two reasons for this. First, the process is slight, i.e., the slow flows would not result in a marked divergent process. Second, below 200 m the vertical gradients of the properties are small compared with the gradients in the troposphere. Therefore it would be extremely difficult to observe the vertical motion below 200 m depth.

It should be noted that Fig. 6(A), 7(A) and 13 include POG data, whereas the volume transport picture does not. Therefore in a discussion of the relation of the topography of the structural features to the position of the null flow line, these three Figures constitute a semi-independent set of data, and as such impart a greater credence to conclusions than if the structural and dynamic features were based on identical data.

INTENSIFICATION OF ALASKAN STREAM. The strong Alaskan Stream indicates intensification by some force. If the effect is due to Coriolis force, the Alaskan Stream would be an example of westward intensification. However, this current is not the same as other westward intensified flows such as the Gulf Stream and the Kuroshio Current. The latter are formed when a broad westward flowing current turns northward. The Alaskan Stream forms after a broad northward flow turns westward and then southwest.

If it is assumed that at the head of the Gulf of Alaska the current, having turned from north to west, constitutes a westerly flow, then it is possible to investigate the intensification which Coriolis force would cause. Morgan (1956) showed that a wind-driven westerly current could be turned into an intense southward current if there is no boundary on the south. In this case the northern boundary (coast) will constitute a streamline. In the direction of a southward current there is a decrease in Coriolis force. Since the absolute vorticity of the flow must be maintained constant, there must be an increase in velocity shear across the stream. The water "particles" approaching the coast with larger Coriolis force must acquire a larger positive velocity shear than must those approaching with smaller Coriolis force. Then the intensified stream thus formed will have maximum current at the coast.

The absolute vorticity of flow was defined previously as

$$\xi_a = 2\,\Omega \sin \Psi + \xi\,.$$

The relative vorticity of a water element in a streamline is defined as

$$\xi = \frac{\partial v}{\partial n} + \frac{v}{n}\,.$$

where $\frac{\partial v}{\partial n}$ = velocity shear normal to the streamline,

$\frac{v}{n}$ = measure of streamline curvature.

When the radius of curvature of a streamline is large, the term $\frac{v}{n}$ is negligible. Therefore, for straight streamlines,

$$\xi = \frac{\partial v}{\partial n}$$

$$\text{and } \xi_a = 2\Omega \sin \Psi + \frac{\partial v}{\partial n}\,.$$

If absolute vorticity of flow is conserved, then at any point on a streamline

$$\frac{\partial v}{\partial n} + 2\Omega \sin \Psi = \text{constant}.$$

When the flow changes latitude from Ψ_2 to Ψ_1, where Ψ_1 is the lower, then on a streamline

$$\left[\frac{\partial v}{\partial n}\right]_1 + 2\Omega \sin \Psi_1 = \left[\frac{\partial v}{\partial n}\right]_2 + 2\Omega \sin \Psi_2$$

$$\text{or } \left[\frac{\partial v}{\partial n}\right]_1 - \left[\frac{\partial v}{\partial n}\right]_2 = 2\Omega[\sin \Psi_1 - \sin \Psi_2].$$

If the latitude change is small, then the increase in velocity shear normal to the streamline which must be acquired by the flow when it reaches the lower latitude is

$$\frac{\Delta v}{\Delta n} = 2\,\Omega\,\delta\Psi\,\overline{\cos \Psi}\,.$$

As is indicated by Fig. 35, the 0- to 2000-db volume transport flow between U of W Sta. 23 and 25 formed part of the flow between U of W Sta. 45 and 46.

TABLE II. Shear increase normal to two flow lines of the Alaskan Stream due to latitude changes.

Latitude change		Shear increase
From	To	
		cm/sec/km
58°00′N (B′)	54°25′N (A′)	0.50
56°30′N (B)	53°45′N (A)	0.40

Only two of the flow lines are shown in Fig. 35. They were essentially straight between the two station pairs. Therefore, in the direction of flow, the velocity shear normal to the flow line for each flow line must have increased.

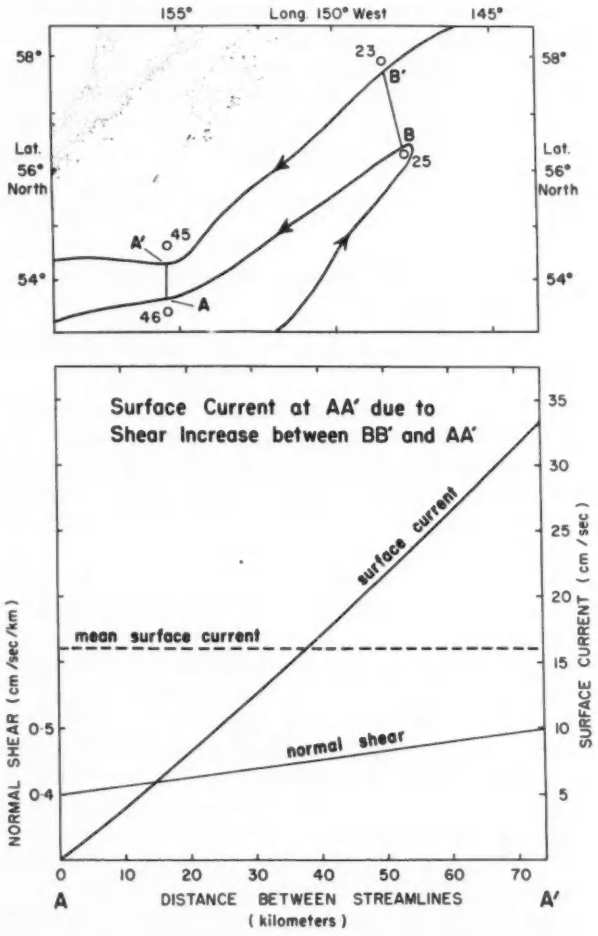

FIG. 35. Surface current across Alaskan Stream due to shear.

The theoretical shear increases normal to the flow lines for the observed latitude changes were calculated. The results are indicated in Table II.

The shear increase normal to the flow lines at AA′ varied linearly from 0.40 cm/sec/km at A to 0.50 cm/sec/km at A′. The distance between the flow

lines at AA′ was about 74 km. Integration of the shear increase across that distance gave the surface current profile at AA′, due to shear increase between BB′ and AA′. This is illustrated graphically in Fig. 35.

The mean surface current due to increase in normal shear is about 16 cm/sec. This is, theoretically, the increase in mean surface current which should have occurred between BB′ and AA′. But the observed increase in mean surface current between those two traverses was about 4 cm/sec.

Thus the theoretical mean surface current increase is four times as large as the observed increase. If it is postulated that friction inhibits intensification by as much as 50%, the theoretical current increase will still be roughly twice the observed increase. The large discrepancy may be due to either of the following:

(a) absolute vorticity of the flow was not conserved and the theoretical calculation is meaningless;

(b) absolute vorticity of the flow was conserved but the theoretical analysis is faulty.

The latter is considered more probable, as the following continuity argument indicates.

The distance across BB′ was about 160 km. The mean surface current there was about 9 cm/sec. The distance across AA′ was about 74 km. Then continuity of volume demands that the mean surface current at AA′ was about 19 cm/sec. If this was the case, the increase in mean surface current between BB′ and AA′ would be about 10 cm/sec. That would agree much better with the theoretical increase of 16 cm/sec.

It is suggested that volume transport — not surface current — should be used to assess intensification. Such an analysis involves a third dimension, depth; and becomes rather more than the scope of this paper. However, the simple continuity argument suggests that absolute vorticity of flow is conserved.

CURRENT IN THE VICINITY OF SANAK ISLAND. At Long. 161°W, the northernmost station of depth 2000 m (extrapolated) was U of W Sta. 52. Between that station and the southern boundary of the Alaskan Stream the volume transport of water westward was about 8.6×10^6 m^3/sec. But the circulation in the Gulf of Alaska comprised at least 17.5×10^6 m^3 of water per second. Then continuity of volume required that at least 8.9×10^6 m^3 of water pass west per second between Sta. 52 and the Alaska Peninsula. Again "at least" must be used in discussing transport for here no estimations have been made of contributions to the total circulation by currents along the shores, or by river discharge into the Gulf of Alaska. It follows, however, that a rough estimation of the mean current between U of W Sta. 52 and the Alaska Peninsula is possible.

Figure 36 depicts the profile of the bottom between Unimak Island and U of W Sta. 52. The cross-sectional area of the water in this section is 23.9×10^6 m^2. Then the passage of at least 8.9×10^6 m^3 of water per second would require a mean current of at least 37 cm/sec. Such a mean current is not unreasonable, but should be indicated by large slopes of such surfaces as σ_t or δ. That this

situation existed is verified by the inset to Fig. 36, which shows in section the distribution with depth of the δ surfaces between Sta. 51, 52, and 53. Station 51 was 27.8 km north of Sta. 52. The slope of δ surfaces was much greater between Sta. 51 and 52 than between 52 and 53, and it was between the latter pair of stations that a maximum mean current of 24 cm/sec occurred.

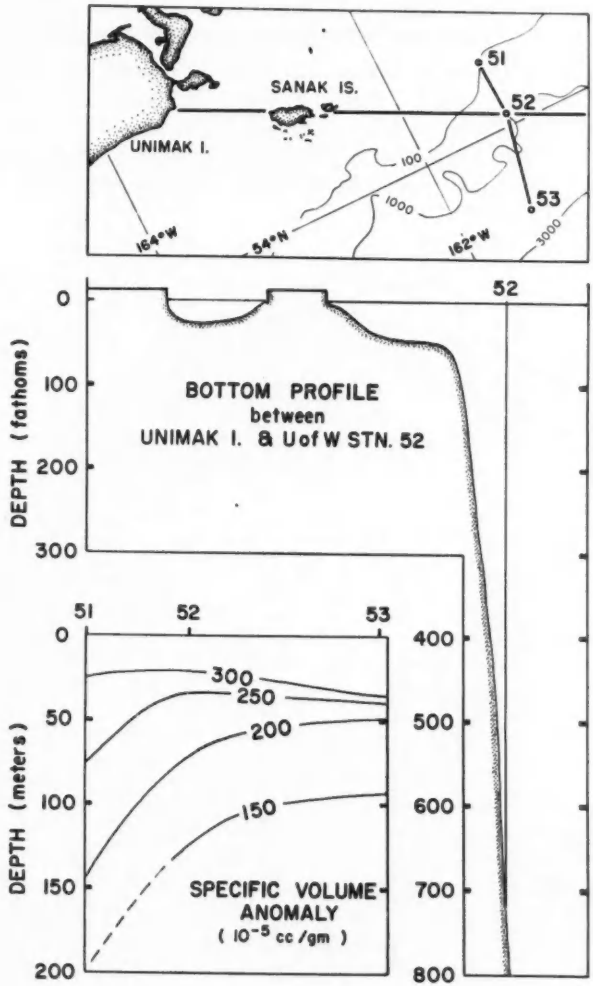

FIG. 36. Bottom profile between Unimak Island and U of W Sta. 52; and distribution with depth of specific volume anomaly (δ) north and south of U of W Sta. 52.

That a strong coastal current exists is verified by the United States Coast Pilot 9 — Alaska (United States Department of Commerce, 1955), from which the following are quoted:

> "A continual current of considerable strength follows the coast all the way from Shelikof Strait to the Aleutian Islands."
> "The coastal current searches out all passages, large and small, between and around the many islands, and in some of them it becomes strong enough to be important."
> "On three runs between Chirikof Island and Castle Rock, a survey ship experienced a southerly set indicating an average strength of current of 1½ knots." [75 cm/sec.]

INFLUENCE OF BOTTOM TOPOGRAPHY. The mean volume transport of water above 2000 m in the center of the Gulf Alaska suffered two marked directional changes (Fig. 32). The first occurred at Lat. 51°N, where the flow curved first to the right and then back again in its northward travel. Further north and east, at Lat. 54°N, a sharp current deviation to the right occurred and immediately

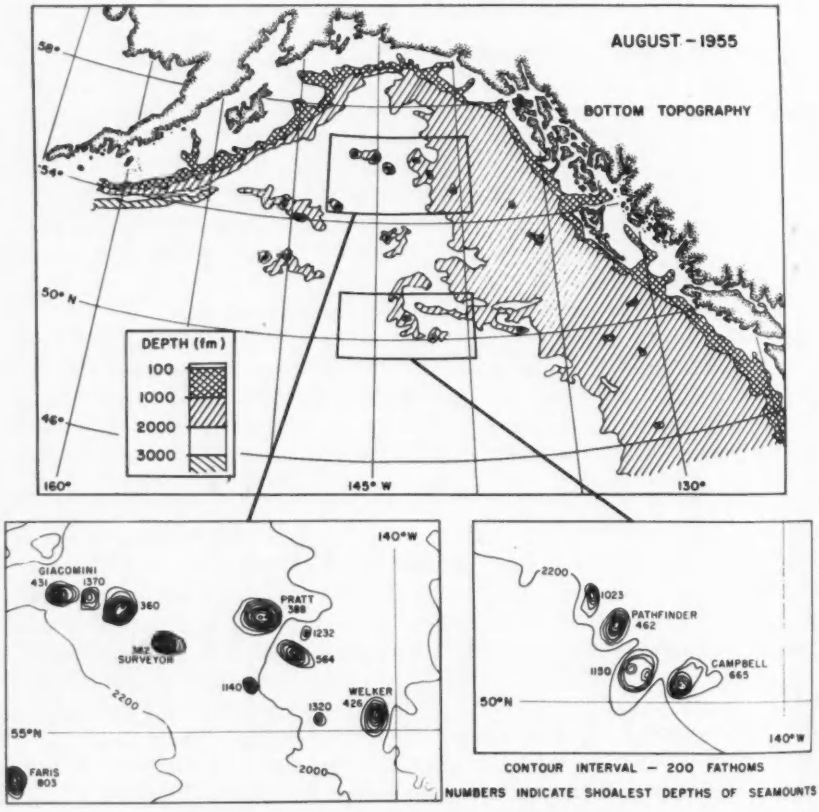

FIG. 37. Bottom topography and seamount chains.

to the north the flow turned west. In the center of the hairpin-like curvature thus formed was a small cyclonic eddy. Such deviations in the direction of volume transport are rather marked to have origin in some non-mechanical process (e.g. thermal factors). Therefore a consideration of a mechanical process leading to current direction changes is necessary for explanation of observations.

Shown in Fig. 37 is the bathymetry of the Gulf of Alaska. Superposition of the volume transport pattern on that of the bathymetry clearly indicated that the two changes in direction of the flow occurred above chains of seamounts. It is therefore expedient to investigate the influence bottom topography on the direction of the transport.

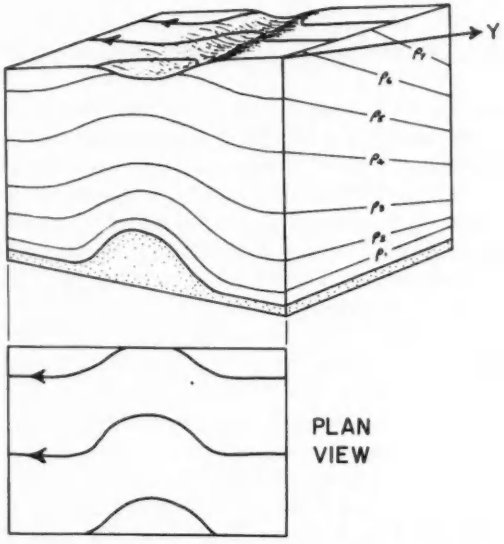

FIG. 38. Deflection of current by a submarine ridge.

Sverdrup *et al.* (1942) explained topographical effects by taking into account the Coriolis force and the vertical stratification of the water masses. His reasoning is illustrated schematically in Fig. 38, a three-dimensional diagram depicting the deformation of the isopycnic surfaces (ρ) and of the open isobaric surface of the sea which would be caused by current crossing an underwater ridge. At some distance in front of the transverse ridge, where the bottom is horizontal, the isopycnic and isobaric surfaces are horizontal in the layer adjacent to the bottom, where it is assumed that there is no current. With increasing distance from the bottom the isopycnic surfaces slope, rising from right to left for an observer looking in the direction of the current, while the isobaric surfaces, and along with them the open surface of the sea, assume a slope contrary to that of the isopycnic surfaces.

As the stream approaches the submarine ridge, the isopycnic surfaces in the bottom sub-layer curve up over the ridge. The isopycnic surfaces in the higher layers of the water will also be lifted upwards. This effects a lowering of the isobaric surfaces, and of the sea surface itself, along the course of the current, in such a way that over the ridge there must be a trough-shaped depression in the sea surface. Therefore, as the current approaches the ridge it will deviate more and more to the right and will reach its maximum displacement over the crest of the ridge. Beyond the crest of the ridge a deviation back to the left will occur and at some distance away the current will once again assume its original direction.

Since the deflection is in the same direction at all depths, it is readily seen that mean volume transport integrated from surface to bottom would suffer the same deflection.

In order to apply Sverdrup's theory, it is assumed that a current crossing a transverse chain of seamounts suffers the same change in direction as is effected by a ridge.

With that assumption it is readily apparent that Sverdrup's theory explains the two major current deviations. The short chain of seamounts, centered roughly at Lat. 51°N and Long. 143°W, caused the flow to bend to the right as it approached the chain. Over the bottom elevations the maximum deflection occurred and north of the chain the current curved back to the left and then straightened out. The flow deviation at Lat. 55°N was of the same character and was centered on the northern band of seamounts. Therefore it is concluded that the flow deviations were due to the effect of bottom topography.

A different explanation of the effect of bottom topography on the direction of ocean current has been presented by Shtokman (1947). He argues that if ocean currents are affected by the wind, then the pressure gradient cannot exist completely independent of the wind. In that case, because of the rotation of the earth the slopes of the isobaric surfaces observed will be the result of an adaptation of the pressure gradient to a Coriolis force, set up by an already existing current produced by the wind. It follows that the pressure gradient and density distribution in the depths of the water would be a secondary effect of the wind. Then Shtokman's theory applies to a wind-driven circulation. The current deviations are related to the bottom morphology and vorticity of the wind field.

It has already been indicated that the circulation in the Gulf of Alaska was influenced but not driven by local winds. Also, as previously discussed, the summer surface wind distribution exhibits no strong, prevailing winds. These two facts preclude application of Shtokman's theory for explanation of the current deviations.

Nowhere thus far in the discussion of the effect of bottom morphology on currents has the depth of the influencing seamounts been considered. Shown in Fig. 39 are the 2000- and 3000-m contour lines of the seamounts of the northern and southern groups. The solid areas or blackened areas indicate where depth is between 2000 and 3000 m, and the inner stippled areas appearing at some seamounts indicate depth less than 2000 m. These seamounts occur over those parts of the abyssal plain of the northeast Pacific Ocean where its depth is 2000

to 2200 fathoms (3700 to 4000 m). It is obvious that if a current was limited to 2000 m, it would not be affected as much by the bottom morphology as a current that extended to 3000 m or more.

The implication of the last statement is worthy of consideration. The possibility of motion below 2000 m was inferred in the analysis of specific volume

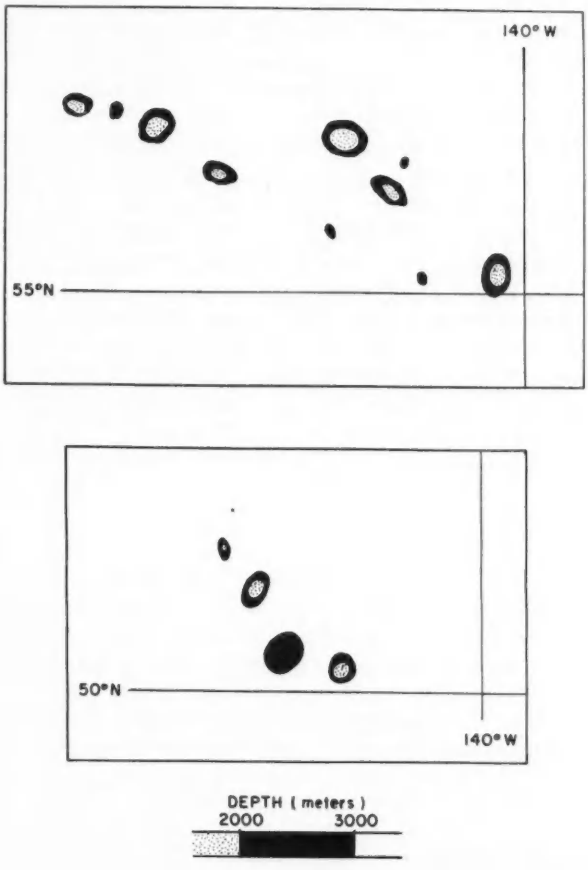

FIG. 39. The 2000- and 3000-m depth contours of the seamount chains.

anomaly at and below 2000 m (see page 616). But no guess of the direction of deep flow could be made. However, the observed bottom topographical effects suggest that the deep current is in essentially the same direction as the surface current, at least in the vicinity of the seamount ranges.

SUMMARY AND CONCLUSIONS

The volume transport of water in the Gulf of Alaska was characterized by a slow northeast movement through the center of the region. This flow was about 13×10^6 m^3/sec. Near the head of the Gulf of Alaska the flow was joined by the transport adjacent to the Canadian coast (4×10^6 m^3/sec) and the whole turned westward and then southwest, all the while undergoing acceleration. The strong southwest flow is named the *Alaskan Stream*. In the southeast part of the region, volume transport was the upper half of a cyclonic eddy which comprises about 3×10^6 m^3/sec. North of the cyclonic eddy was an intense clockwise eddy of 8×10^6 m^3/sec. Between this eddy and the northerly Canadian coastal current was an elongated cyclonic eddy of 1×10^6 m^3/sec.

The volume transport integrated over 2000 db had the same direction as the surface wind only in the center of the region. Flow in the upper 200 m of depth was influenced but not controlled by the local wind field. Thus the circulation in the Gulf of Alaska was not wind-driven locally at the time of these data.

The Alaskan Stream may conserve absolute vorticity, i.e., the intensification may be due only to the changing Coriolis parameter.

The existence of motion below 2000 m was indicated in the analysis of the data. This view is supported by consideration of the influence of bottom topography on the direction of flow, since the seamount chains of the region would affect a current more if it extended below 2000 m. Taken together, these two lead to the conclusion that the inferred current below 2000 m has the same direction as the observed volume transport of the upper 2000 m, at least in the vicinity of the seamount chains.

ACKNOWLEDGMENT

The author wishes to express his sincere appreciation to Dr J. P. Tully, of the Pacific Oceanographic Group of the Fisheries Research Board of Canada, and to Dr G. L. Pickard, of the Institute of Oceanography at the University of British Columbia, for the continuing support and helpful criticisms, requisite for the preparation of this report; to Dr N. P. Fofonoff, of the Pacific Oceanographic Group, for mathematical direction; and to those members of the Pacific Oceanographic Group who assisted in the actual physical construction of the thesis.

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Current Measurements in Knight Inlet, British Columbia[1]

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ABSTRACT

One of the features of the circulation in an estuary is the net outflow in the surface layer of the fresh water discharged into the estuary together with an appreciable volume of salt water entrained. Continuity considerations require that there be an inflow of salt water to compensate for that taken out in the surface. In a shallow estuary, such as Chesapeake Bay, this results in a two-layer flow, out at the surface and in below it.

In a deep estuary, the questions arise whether or not it also possesses this simple two-layer flow and what is the depth and extent of the inflow. Measurements have been made in several inlets in the British Columbia coast to obtain information about the circulation in a deep estuary. Preliminary experiments were made in Toba, Bute and Knight Inlets, the series made in Knight Inlet in July 1956 being the most complete. The techniques employed and the results obtained are described and discussed.

In a shallow section (75 m), in-and-out (flood-and-ebb) flow occurred in phase from surface to bottom, with a net outflow in the upper half and inflow below this. In the presence of an up-inlet wind, the flow in the surface few metres reversed and became up-inlet, with an increased outflow below it.

In a deep section, both oscillatory (tidal period) as well as net currents occurred at all depths from the surface to 300 m (relevant bottom depth was 350 m). In this deeper section, the oscillatory components were not in phase from surface to bottom, and the net flow showed a three- or four-layer pattern, rather than the simple two-layer pattern which has previously been assumed to exist. The wind had a marked direct effect on the upper layers to a depth of about 10 m and possibly deeper.

The movement of the ship while at anchor was monitored and found to be considerable. Most of the current observations were corrected for ship motion before analysis.

Calculations of the net fresh water transport (in the upper layer) give reasonable values but similar calculations for the deep water show a net transport which is not to be expected. This apparent net transport may be a consequence of assuming that the current profile across the entire inlet is the same as that in the centre where measurements were made. Other possible sources of error are suggested. In addition, several recommendations are made for future work.

INTRODUCTION

The Institute of Oceanography of the University of British Columbia has carried out a study of coastal inlets of British Columbia over several years. These inlets (Fig. 1) are deep indentations in the shoreline. They are long and narrow with steep sides. The bottom topography is characterized by a deep basin that is often two to three times the depth of the outside passages and coastal shelf regions. The deep basin of the inlet and the shallower passages beyond the inlet mouth

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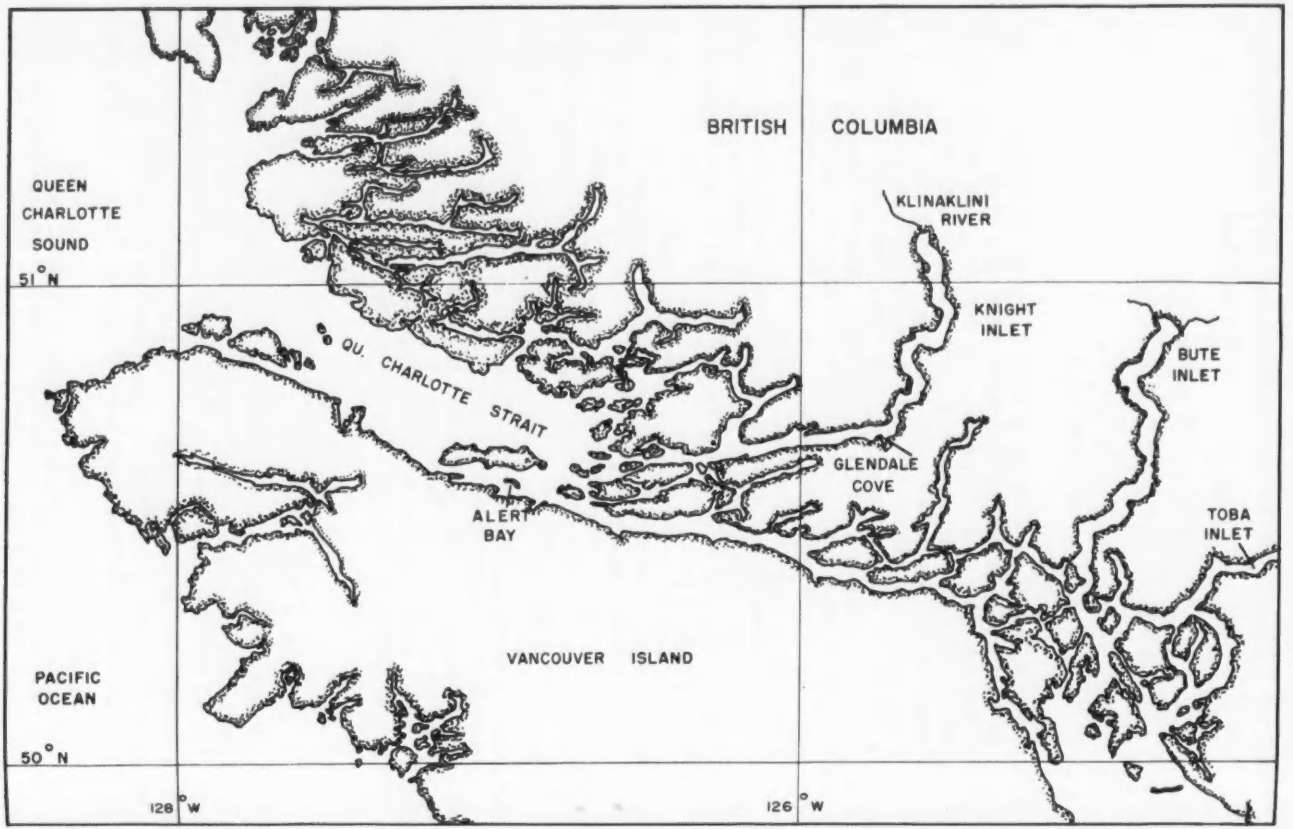

FIG. 1. Location of Knight Inlet, British Columbia.

are usually separated by a sill, or shallower section where the depth is about half that of the outside passages. In these inlets the distribution of properties such as salinity, temperature, and oxygen content has been determined for the summer period.

The salinity distribution provides some information about circulation in the inlets. The circulation or water movements within the inlets, if fully understood, would help in understanding the sources and movement of nutrients for biological activity. It also would assist in determining the distribution of particulate material and possible pollutants.

The first fact provided by observation of the salinity distribution is that almost all fresh water emptied into an inlet by rivers (principally at the head of the inlet) stays in the surface layer. The fresh water flows out over higher salinity sea water. The salinity of the surface layer increases from the head to the mouth and therefore salt water must be mixed upward into the surface layer and carried seaward. In order that there be continuity of the fresh water flow, the speed of the down-inlet flow of the surface layer must increase towards the mouth. In order to replace the salt carried seaward in the surface layer there must be up-inlet flow of sea water at depths below the surface layer. Extensive surveys of a shallow east-coast estuary (Pritchard, 1952) where the water is slightly less stratified bear out these ideas and dynamical studies of deep inlets have been based on the two-layer model (Cameron, 1951; Stommel, 1951). However, in deep inlets little was known of the vertical distribution of net currents (non-periodic) or of tidal currents (periodic) prior to the observations described in the present paper.

There are some difficulties in carrying out a current measurement programme in these deep inlets. Experiments were made in each of the three years 1952, 1953 and 1955 in Bute, Toba and Knight Inlets to find a suitable location for measurements, to determine the best technique for anchoring, to determine the magnitude of currents to be measured, and to experiment with current-measuring devices.

The 1956 data from Knight Inlet, with which this account is concerned, represent the most recent experiments in this series. The data serve as the basis for an analysis of the techniques employed and for an analysis of the currents in order to determine the influence of tide, wind, and runoff.

INLET DESCRIPTION

In general characteristics Knight Inlet (Fig. 2 and 3) is typical of those in British Columbia (Fig. 1). It is a coastal indentation with a length of 102 km, or 55 nautical miles (n. miles), and an average width of 3 km (1.6 n. miles). The average mid-inlet depth is 420 m (1380 feet) and the maximum is 550 m (1800 feet). It has two sills in its length, 74 and 110 km from the head of the inlet. The outer basin between these two sills has irregular topography but does not exceed 250 m in depth. The inner basin between the inner sill and the head is deeper and contains the maximum depth (Pickard, 1956). The outer sill depth is 67 m and the inner one 63 m.

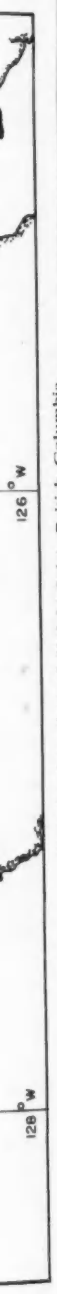

FIG. 1. Location of Knight Inlet, British Columbia.

The inlet is a positive, fjord-type estuary (Pritchard, 1952) in consideration of its depth, sills and average salt content (less than that of the adjacent sea). The fresh water is supplied largely by river runoff introduced at the head by the Klinaklini River.

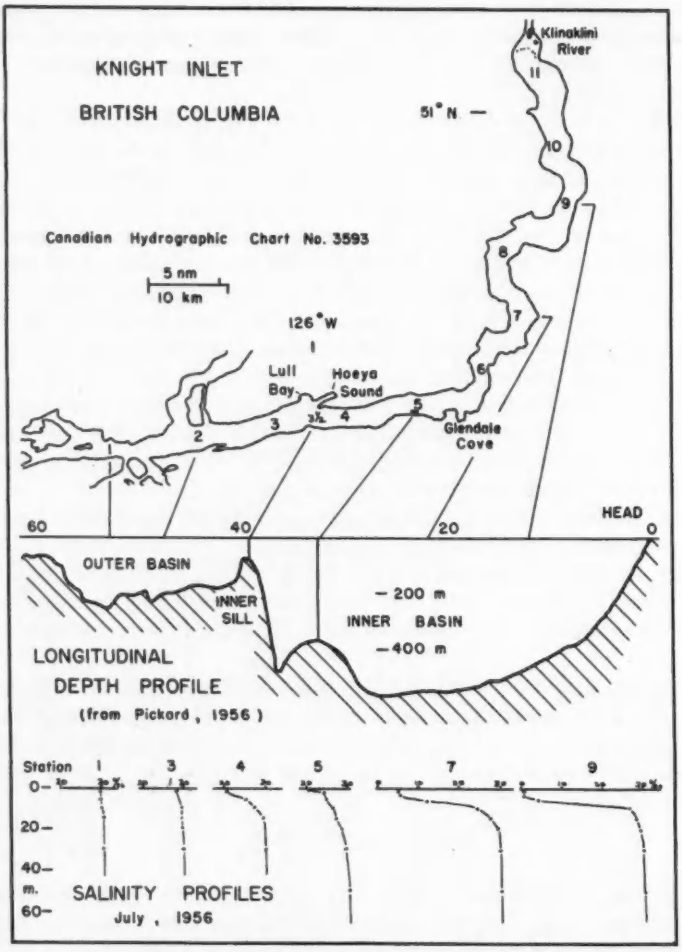

FIG. 2. Knight Inlet, British Columbia: Plan, station positions, longitudinal profile and salinity–depth profiles.

This river runoff is at a maximum in June due to melting of the snow and ice at higher altitudes. An estimate of the mean monthly runoff has been made from rainfall and watershed data (Pickard and Trites, 1957). For June and July the values estimated are 790 and 615 m^3 per second respectively.

A series of salinity profiles down the length of the inlet is plotted in Fig. 2. These are taken from data obtained during the two days following the last current measurement in 1956. The water begins as a highly stratified, two-layer system at the head and becomes nearly homogeneous in the outer basin. The fresh water is chiefly in the upper 20 m, though there is still a gradient in salinity below this.

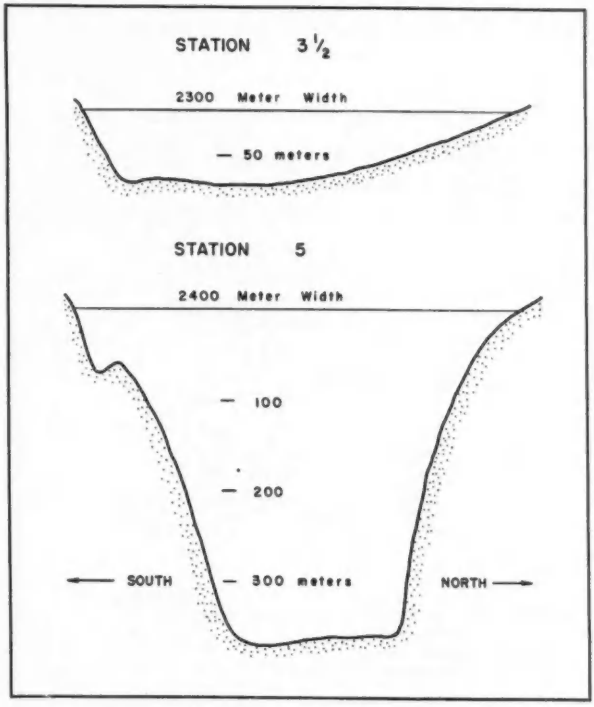

FIG. 3. Transverse section at Stations 3½ and 5, Knight Inlet.

The fresh water has salt water mixed upward into it as it moves down the inlet. The upper layer eventually reaches a salinity close to that of the sea water at the mouth.

The two stations (No. 3½ and 5) at which current measurements were made are in the straight reach of the inlet (Fig. 2). A straight reach was chosen because previous measurements in a sinuous inlet (Bute Inlet) were found very difficult to interpret. Station 3½ was on the inner sill, or slightly up-inlet from the shallowest part (Fig. 4). Station 5 was situated 15 km (8 n. miles) up-inlet from Station 3½

over the deeper basin inside the inner sill. Transverse profiles of the inlet at these stations are shown in Fig. 3. As well as the difference in depth at these two stations, the depth profile at Sta. 5, being symmetrical about the centre-line, is different from that at Sta. 3 where it is asymmetrical about the centre-line.

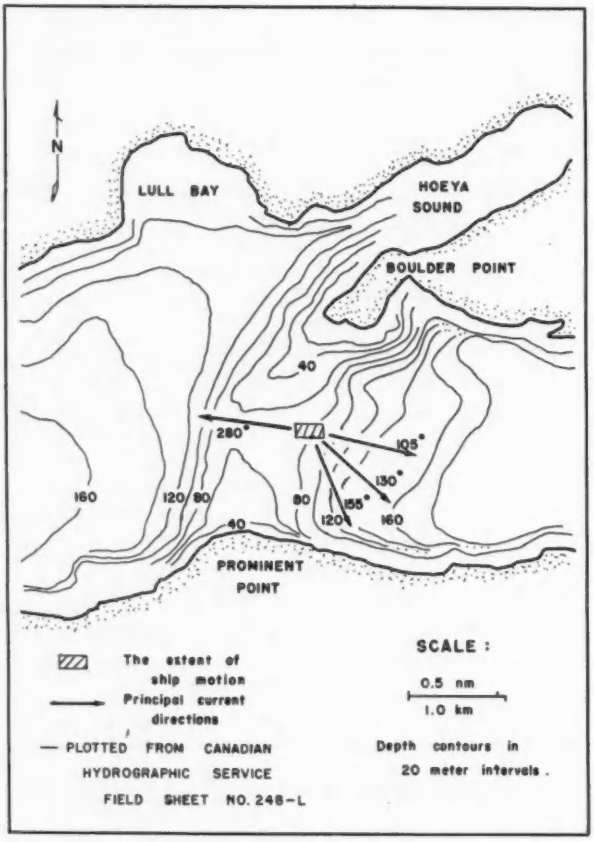

FIG. 4. Shoreline and bottom contours near Station 3½, Knight Inlet.

Tides in this region are of the semi-diurnal mixed type with a maximum range of about 5 m. The nearest continuously recording tide station to Knight Inlet is at Alert Bay, about 74 km (40 n. miles) from the region where the current data were obtained. Alert Bay is near the network of channels into which the inlet empties.

The nearest tide station referred to the Alert Bay tide predictions is Glendale Cove, about 8 km (5 n. miles) up-inlet from Station 5. For Glendale Cove there is no time difference from Alert Bay in high or low water, but there is a mean ratio of rise for high tide given as 1.15 (Canadian Hydrographic Service, 1956). The tides indicated on the various graphs are those predicted for Alert Bay.

During the period of these observations the prevailing and the strongest winds were westerly, or up-inlet. The one exception was during the first 24 hours on Sta. 5 when a steady 10-knot wind blew down the inlet. The up-inlet winds followed a diurnal cycle with a minimum between 0600 and 1200 hours and a maximum between 1600 and 2000 hours. The maximum up-inlet wind in each case was over 20 knots.

EXPERIMENTAL PROCEDURE

Measurements were taken from the research vessel, H.M.C.S. *Cedarwood,* a wooden ship of 51 m length, 9.2 m beam and 4.5 m draft. A single anchor was used as previous attempts to anchor bow and stern had proved unsuccessful.

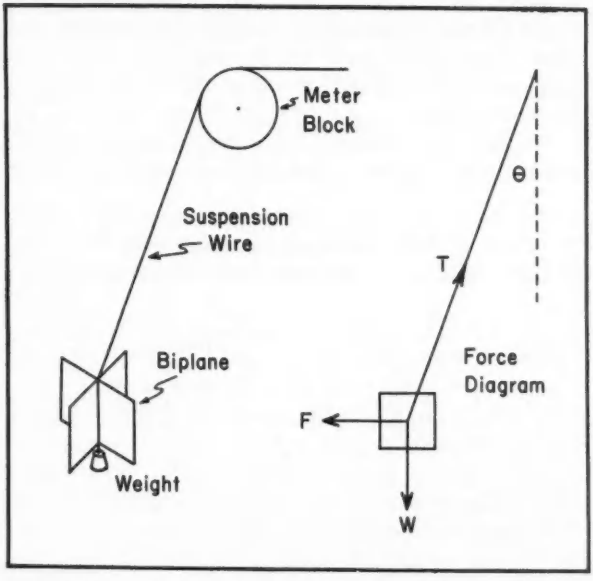

FIG. 5. C.B.I. current drag: schematic and force diagrams.

Current profiles were obtained from the surface to 20 m with a Chesapeake Bay Institute (C.B.I.) current drag (Burt and Pritchard, 1951) suspended on a $\frac{3}{32}$-inch diameter wire (Fig. 5). For the first and second anchorages measurements were made every half hour, and every hour on the third anchorage. The drag had planes $1 \times 1\frac{1}{2}$ feet, and added weights of 10, 20 or 40 pounds were used.

Measurements with the Ekman current meter were taken in the remainder of the water column every hour. At Sta. 5 the Ekman current meter measurement depths were 50, 100, 200 and 300 m. At Sta. 3½ the depths were 10, 20, 40, 60 and 70 m. It will be noted that there is an overlap of C.B.I. drag and Ekman meter measurements at the 10- and 20-m depths on Sta. 3½. These measurements served to compare the two instruments.

For the meter used in this experiment the threshold velocity required to overcome friction was 1.8 cm/sec. Experience with calibration of these instruments shows a possible error of about 3% in readings. The accuracy in the direction indication is about ± 5° for reasonably large currents but there is a larger uncertainty in small currents (Tabata and Groll, 1956).

Error in indication of the water current is introduced by horizontal ship movement during the current measurement. The Ekman meter reads the vector sum of the actual water current relative to the earth and an apparent current due to the ship velocity relative to the earth. Since the ship velocity is a significant percentage of this reading (see discussion of ship motion) the ship's movement was monitored to permit correction.

At the beginning and end of each Ekman current reading a 3-point sextant fix was taken on shore marks whose positions were determined during the anchorages. These shore marks were usually prominent rocks white-washed for daylight visibility and marked by oil lanterns at night. Only when rain was heavy were these stations not visible.

A point of distinction between drag measurements and Ekman meter measurements is that the Ekman measurements are values integrated over 2 min

TABLE I. Periods of observation, Knight Inlet, 1956.

Station:	5	3½	5
Duration of anchorage:	1500 July 4 to 1500 July 6 (48 hours)	1800 July 6 to 1800 July 8 (48 hours)	2100 July 8 to 1600 July 11 (67 hours)
No. of C.B.I. drag profiles to 20 m:	90	96	64
No. of Ekman meter profiles:	48	48	63

(in most cases) whereas drag measurements are obtained in 10 to 15 seconds. The latter more closely approximate instantaneous readings.

The period of observation extended from July 4 to 11, 1956, as shown in Table I.

A bathythermograph (BT) cast to 270 m was made hourly at Sta. 5 and to 70 m hourly at Station 3½. The occasional 20-m cast was made with a special BT to determine the surface temperature structure in more detail.

Hourly meteorological observations included the wind velocity, air temperature (wet and dry bulb thermometers), barometric pressure, cloud type and cloud cover, visibility and sea state.

On the 2 days following the last current station, oceanographic stations were taken along the length of the inlet to determine the water structure.

In numerous instances below there will be reference to a "calculated" tidal current as opposed to the observed currents. This "calculated" current was deduced from predicted tides on the basis of the assumptions:

(1) that the real tide was as predicted,

(2) that the whole water surface of the inlet rose and fell uniformly,

(3) that the tidal current necessary to provide the water for filling (or emptying) the tidal prism was uniform across the entire section of the inlet.

The close correspondence between the actual tide records and predicted tide heights at Alert Bay lend support to the first assumption. Early investigations by Dawson (1920) support the second. Evidence from the observations suggests that the validity of the third assumption is open to question.

DATA TREATMENT

Ship Motion

The sextant readings on shore stations and the data determining the shore stations positions were used to calculate the ship's velocity during current measurements. They were also used to determine the large-scale movements of the ship from hour to hour.

The shore stations were arranged as shown in Fig. 6, so that one angle (θ_1) was measured between two stations on one shore, and the other (θ_2) between two stations one on either shore.

To determine the gross ship movement it was sufficient to plot positions with a three-arm protractor. For short-period (e.g. 2-min) movements the protractor was not sufficiently sensitive and an alternate procedure was used as follows.

A change in θ_1 was chiefly a measure of the cross-inlet movement and a change in θ_2 was chiefly a measure of the along-inlet movement. The displacement, $\triangle S$, was approximately related to the mean $\bar{\theta}$ of the two fixes on the same stations, the distance L between the two shore stations, and the change $\triangle\theta$ in angle between fixes, by:

$$\triangle S = \frac{L}{4} \cdot \operatorname{cosec}^2 \frac{\theta}{2} \cdot \triangle\theta.$$

This equation could be applied to either of the components of movement (either across or along the inlet) and was based on two assumptions:

(1) that $\triangle S$ was small compared to L, and

(2) that the ship (point of observation) was fairly close to the right bisector of the line joining either pair of shore stations. Any more rigorous formula to fit the actual situation of stations required an uneconomical amount of labour for reducing the data.

The ship's velocity during current measurements was determined from the time between sextant fixes (the activation time of the current meter), and the

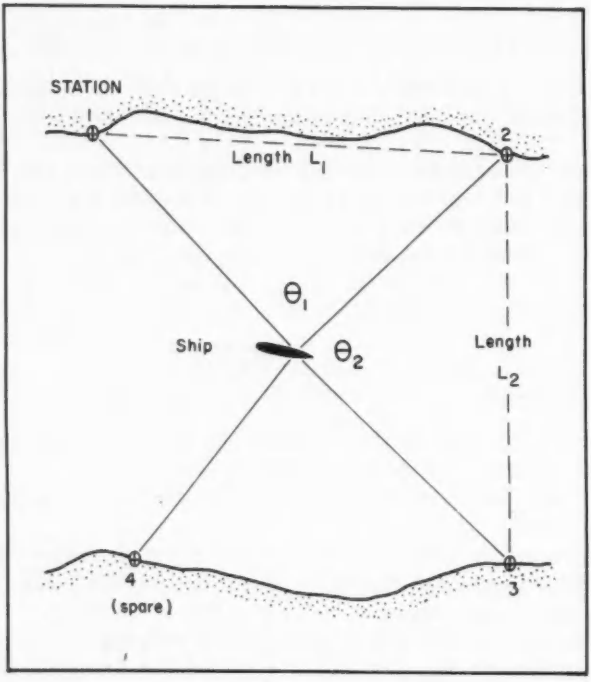

FIG. 6. Typical arrangement of shore stations for ship position determination.

distance the ship had moved as determined from the fixes in the above manner. The formula above was used to determine the two components of the movement and these were combined to give a vectorial displacement.

Because of the rugged nature of the coastline in this inlet, the choice of position of the shore stations was limited. Thus the conditions stated above were not exactly met and for this reason the error in the along-inlet direction is put at 5 to 10%. For the same reason the error in the cross-inlet component of the ship motion must be put at 15 to 20%. The reason for the large possible error

in the cross-inlet component lies in the shoreline irregularities. The station had to be placed so that, at times, the ship moved away from the right bisector. Thus any cross-stream currents deduced from currents corrected for ship motion may include an error of the above proportion (15 to 20%) of the ship speed.

There is the assumption implicit here that the meter moves with the ship. This is an assumption that is usually made, but seldom justified. The following is an attempt to put an upper limit on the possible error that might be incurred by making the above assumption.

If the assumption does not hold, then there will be relative movement between the meter and the ship. This would result in a change in the suspending wire angle from the vertical. During Ekman current measurements, the wire angle was checked visually. In a few cases at Sta. 3½ for strong currents it was necessary to let out more wire to achieve the required depth. In most cases, however, the wire did not deviate conspicuously from the vertical. It is considered that deviations less than 5° from the vertical might have gone unrecorded. This angle, combined with an average ship movement of 11 m (Sta. 5) over a meter activation interval of 2 min, shows that the meter must partake of at least 75% of the ship movement when it is at a depth of 50 m; or at least 50% at a depth of 100 m. At greater depths the above limit of detection of wire angle change (5°) gives no guarantee that the meter is moving with the ship. Nevertheless the full correction for the ship velocity has been applied throughout this data.

During rain squalls it was not always possible to monitor ship motion and for this reason some of the data presented are not corrected for ship motion. The Ekman reading itself was used if no correction was available. The percentage of uncorrected data the first period at Sta. 5 was 31%, at Sta. 3½, 2%, and in the second period of observations at Sta. 5, 1%. These figures give some reason to consider the data of the first period on Sta. 5 as less reliable than the data for the second period at the same station.

Current Measurements

The currents obtained from the C.B.I. drag and from the deeper measurements were separated into along-inlet (conveniently east–west) and cross-inlet components. For the C.B.I. drag measurements, resolution into components was carried out only for directions greater than 20° from the east–west line because of the ± 10° possible error in the direction estimate.

The C.B.I. drag measurements were first plotted as profiles to interpolate values at standard depths of 2, 4, 6, 10, 15 and 20 m. Ekman meter readings were taken at standard depths. When the wire angle was large, adjustment was made by paying out more wire.

The series of component values for each depth were then plotted against time together with the tide and wind conditions. From these plots and a smooth

curve drawn through the currents obtained, a vertical current profile for the along-inlet component was constructed for each hour and the hourly profiles were plotted as a series.

The net current at each depth was determined by a 25-hour average of the above hourly values to eliminate the tidal currents.

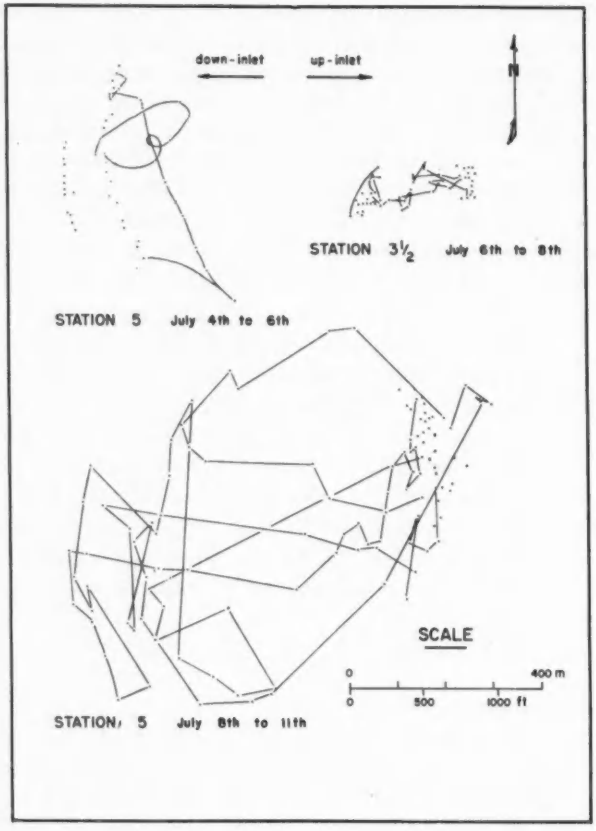

FIG. 7. Successive ship positions (intervals not uniform) while anchored in Knight Inlet.

RESULTS

SHIP'S MOTION

A plot of the ship's position for successive fixes on shore stations shows marked differences among anchorages (Fig. 7). They are of direct significance in the present set of measurements. Though the movements may have been peculiar

to that particular ship they serve as an indication of the type of motion which may occur.

During the first period of observation on Sta. 5, the wind was zero or down-inlet and the surface current predominantly down-inlet. The ship moved on an arc of about 500-m length, thus describing predominant shearing (side to side) motion. On two occasions it sheared and surged (moved up on the anchor) violently off its stable arc. These two periods started during the passage of progressive, internal waves in the lower boundary of the surface layer. When the ship moved off the arc it required 1 to 3 hours to return to it.

During the second anchorage on Sta. 5, the wind and surface current conditions were different, the wind being always up-inlet, and the surface current reversing fairly regularly. Under these circumstances the extent of ship motion was large, covering an elliptical region of 950 by 550 m. The elliptical pattern was bounded by two arcs. The arc on the up-inlet end of this pattern was of smaller length and greater density of positions than the ill-defined arc on the down-inlet end. When the wind and surface currents were in the same direction the ship moved on the smaller arc. The down-inlet end, where wind and surface

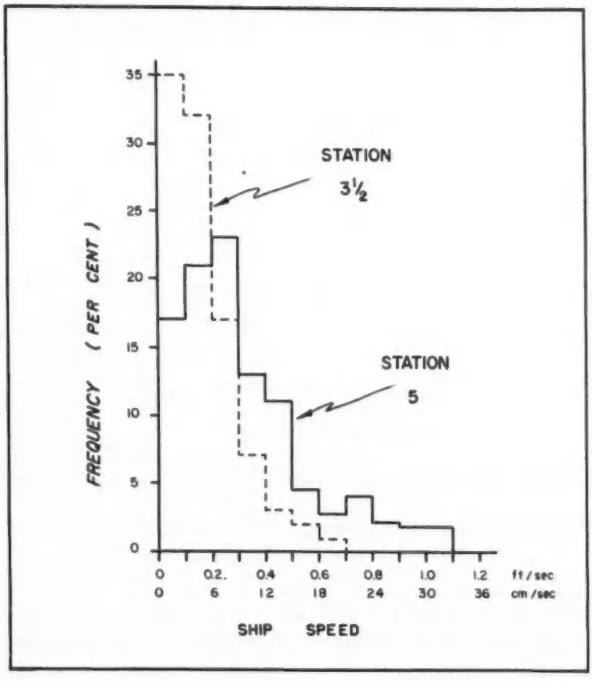

FIG. 8. Frequency of occurrence of specified ship speeds while anchored in Knight Inlet.

current were opposed, showed an ill-defined arc as well as large movement from hour to hour.

The frequency distribution of the ship's speed for the two stations is plotted in Fig. 8. The distributions are skewed as the ship's speed can be great in some cases. Here again, a difference can be seen between Sta. 3½ and 5. The mean

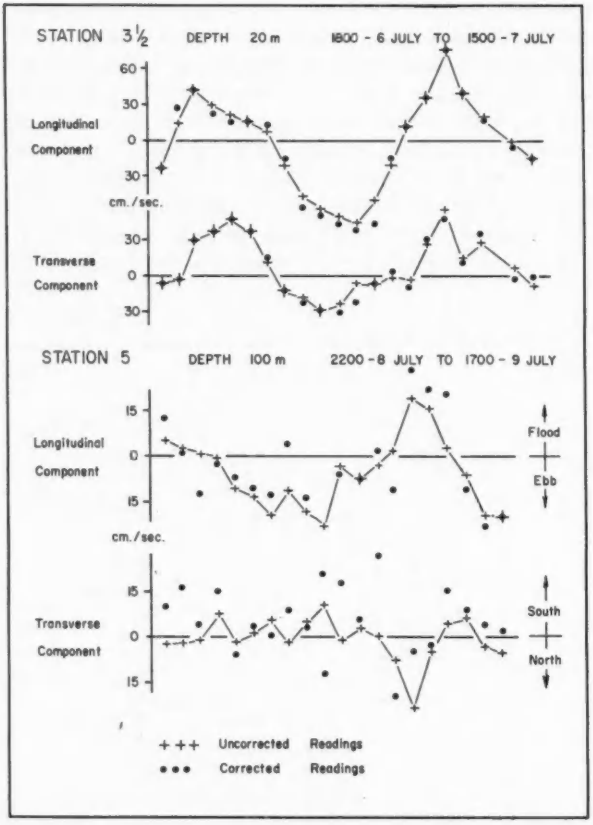

FIG. 9. Comparison of Ekman current meter readings before and after correction for ship motion.

ship speed at Sta. 3½ was 4.5 cm/sec and at Sta. 5 about 7.5 cm/sec. These two means have significance in evaluating the necessity for monitoring ship motion during current measurements.

In Fig. 9 are plotted the Ekman readings as well as the corrected readings for both longitudinal and transverse components of parts of the series at Sta.

3½ and 5. The correction at Sta. 3½ is relatively small. The correction at Sta. 5 is larger and predominantly in the transverse component.

A comparison of mean ship speed in different wind, surface current, and anchorage conditions suggests that the mean ship speed increases with:

(1) increased wind,

(2) decreased surface current,

(3) increased depth at the anchorage,

(4) light cross stream breezes (markedly),

(5) opposing wind and surface current.

Certain of these are obviously interrelated. In particular, in estuaries where tidal currents are present at the surface, a shallow region presents a smaller depth for the anchorage and usually increases the tidal currents. Both these factors act toward decreased ship motion. When the wind and surface current tend towards the same direction there will also be a decrease in the ship movement. In view of the large effect of wind stress on surface currents there is a tendency for the wind and the surface current to be in the same direction.

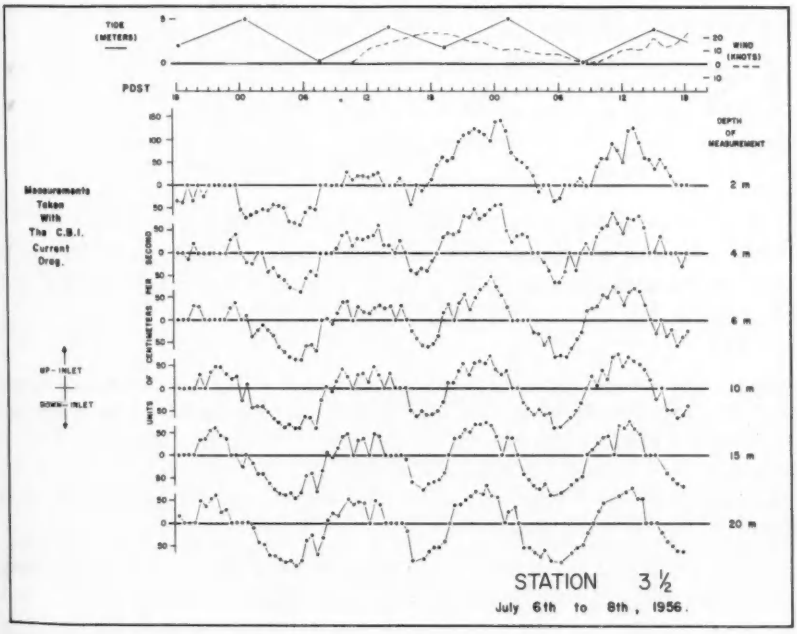

FIG. 10a. Longitudinal components of currents at 2 to 20 m depth at Station 3½, Knight Inlet, 6–8 July, 1956.

DESCRIPTION OF CURRENTS

(1) STATION 3½, JULY 6 TO 8, 1956

A time-series plot of the longitudinal component of the current (Fig. 10a, 10b) shows strong oscillations up- and down-inlet. The times of peak currents and slack water are highly correlated with what would be deduced from the

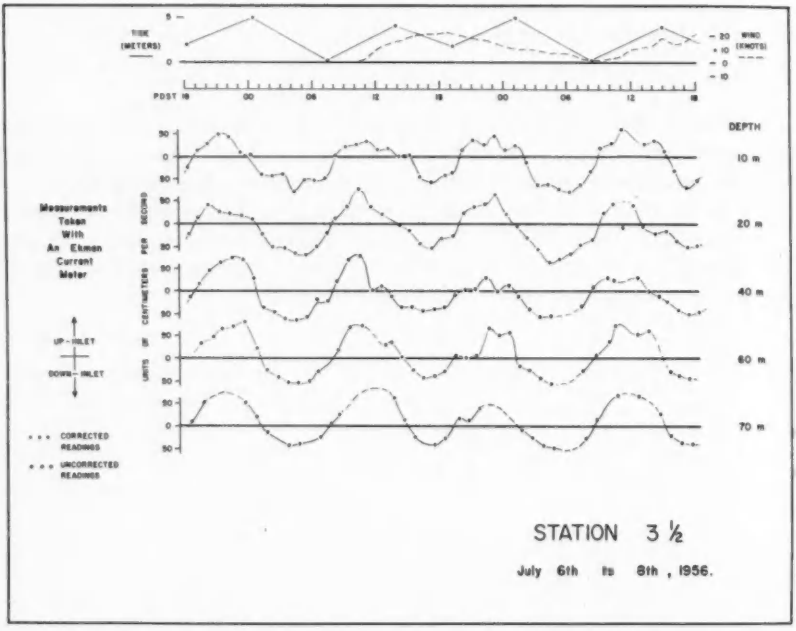

FIG. 10b. Longitudinal components of currents at 10 to 70 m depth at Station 3½, Knight Inlet, 6–8 July, 1956.

predicted tide height curve. The oscillatory currents do not show a smooth sinusoidal variation. There are large irregularities at all depths of measurement.

Since the tide is a mixed semi-diurnal type, a mean tidal amplitude average range of currents can only be used to compare currents at different depths. At this station the range of currents was about 150 cm/sec and nearly constant at all depths with the following exceptions:

(a) at the depth of 2 m where the direct effect of the wind distorted the oscillating currents making an estimate of current range difficult,

(b) at 70 m where the range was about 105 cm/sec or 70% of the currents above it.

In general it appeared that the maximum flood current was more subject to large fluctuations within one flood than was the ebb.

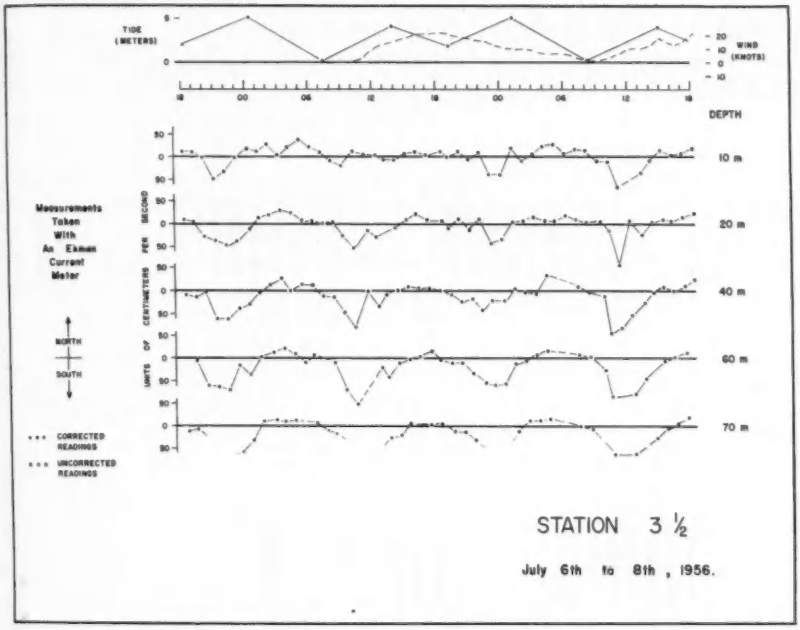

FIG. 11. Transverse components of currents measured at 10 to 70 m depth at Station 3½, Knight Inlet, 6–8 July, 1956.

The transverse component of the current plotted as a time series (Fig. 11) shows asymmetry about a mean current at most depths. In general, the south component on the flood was greater than the north component on the ebb.

The currents on the flood and ebb did not differ in direction by 180°. The flood mean direction was between 103° and 155° true while the mean ebb

TABLE II. Mean current directions, Station Knight 3½.

Depth (meters)	Mean direction (degrees true)			
	First 25 hours		Last 25 hours	
	Flood	Ebb	Flood	Ebb
10	104	286	103	278
20	125	278	103	282
40	127	273	155	274
60	135	277	136	271
70	134	283	129	273

direction was between 270 and 285° true for the whole anchorage. Table II summarizes the data.

Dealing now with only the longitudinal component, it is seen that the plot of the series of hourly profiles (Fig. 12) is naturally divided into two periods; the first with no wind, and the second with varying up-inlet winds.

During the first period the column of water below 20 m appeared to move as a unit with a smaller amplitude of motion at 70 m. The current in the region

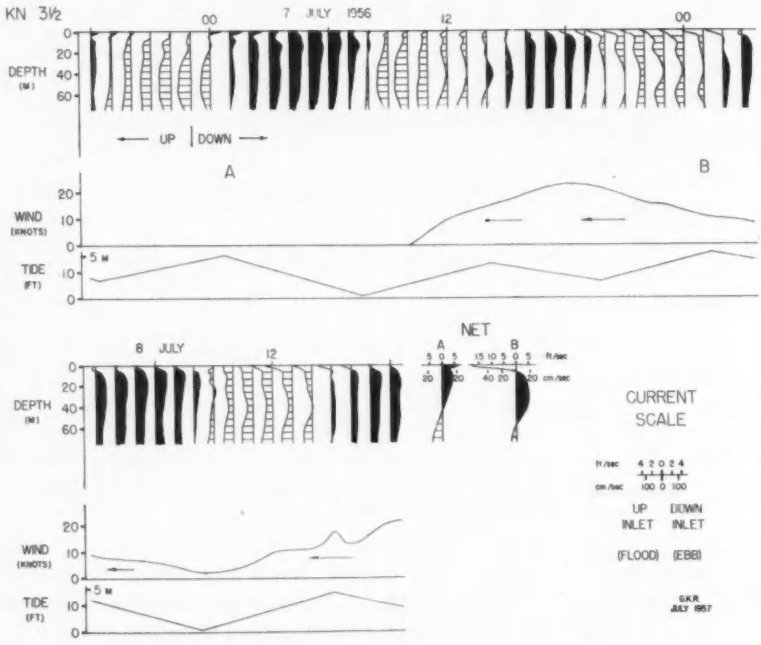

FIG. 12. Hourly profiles of longitudinal component of current at Station 3½, Knight Inlet, 6–8 July, 1956.

above 20 m appeared more complicated. This may be an artifact of observation since there were twice as many measurements in this region. Above 10 m the flood current was markedly less than that of the water below 20 m. The ebb current in the upper 20 m was somewhat larger than the ebb below. There was a minimum in the ebb at 4 to 6 m. This was less evident on the flood. During the second period there were varying up-inlet winds with a maximum speed of 23 knots. There was considerable difference between the flow at the surface and at 40 m. The near-surface current (2 m depth) was reduced to zero on the ebb and was more than

twice the deep current on the flood. There also appeared a minimum at about 10 m which was most marked on the flood.

The 25-hour mean for each depth is plotted in profile for the first and last 25 hours of the anchorage (Fig. 13). These two profiles are quite different. For the first there was an average wind of only 4 knots. There was a net outflow at all depths of measurement down to 40 m while the net flow at 60 and 70 m was up-inlet. There was a significant minimum in the outflow at 4 m or alternatively a maximum in the outflow at 15 m.

For the final 25-hour period the mean wind was 12 knots *up*-inlet and the difference in current from the first period is marked. The surface flow to 6 m was completely reversed. The outward flow at 10 and 15 m was virtually unchanged, but at 20 and 40 m the outflow had increased. The inflow at 60 and 70 m had also been reduced. This resulted in a depth of no net motion at 55 to 60 m rather than 40 to 45 m as occurred during the first 25 hours.

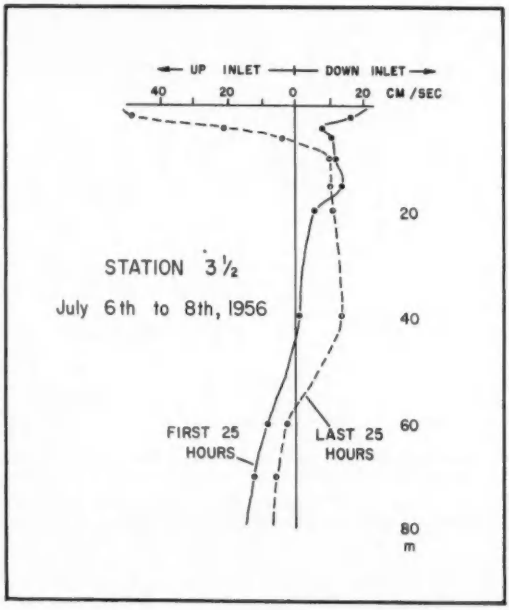

FIG. 13. Net current profiles over first and last 25 hours at Station 3½, Knight Inlet, 6–8 July, 1956.

(2) STATION 5, JULY 4 TO 6, 1956

The time series plot of the longitudinal components of the current is considered first (Fig. 14a, 14b, 14c). At 300 and 200 m the oscillatory current

was predominant but there were sporadic bursts superimposed at 300 m. It appears that the irregularities in the flow occurred usually on the flood current. At 100 m the irregularities nearly obliterated the systematic oscillations and at 50 m the fluctuations were incoherent but just as large as the systematic oscillating currents at 100 m.

The mean range of currents was about 30 cm/sec at 200 and 300 and about 24 cm/sec at 100 and 50 m.

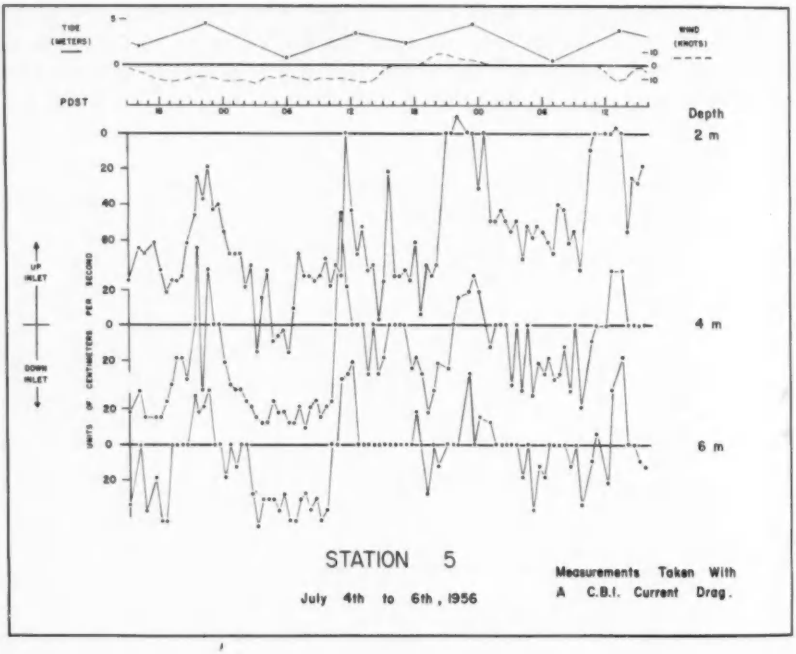

FIG. 14a. Longitudinal components of currents at 2, 4 and 6 m depth at Station 5, Knight Inlet, 4–6 July, 1956.

Before describing the currents in the upper 20 m it should be noted that this anchorage can also be divided into two periods; the first with a 10-knot down-inlet wind and the second period with little wind.

Currents measured in the upper 20 m were much larger than those at the greater depths, ranging from 120 cm/sec down-inlet to 45 cm/sec up-inlet. It is apparent that the net flow was down-inlet at all depths down to 20 m, the magnitude decreasing with increasing depth.

At the 4- and 6-m depths during the first half of the anchorage there were up-inlet surges in current of 60 to 90 cm/sec lasting from ½ to 1 hour in the hour before predicted high water. During the second half of the anchorage this same feature resembled a step function with the up-inlet surge lasting 2 to 3 hours in the 3 hours before predicted high water.

At 10, 15 and 20 m there was an increasing frequency of zero currents measured as depth increased. Currents at these three depths were sporadic, although they tended to coincide with the extremes in current at the 2-, 4- and 6-m depth.

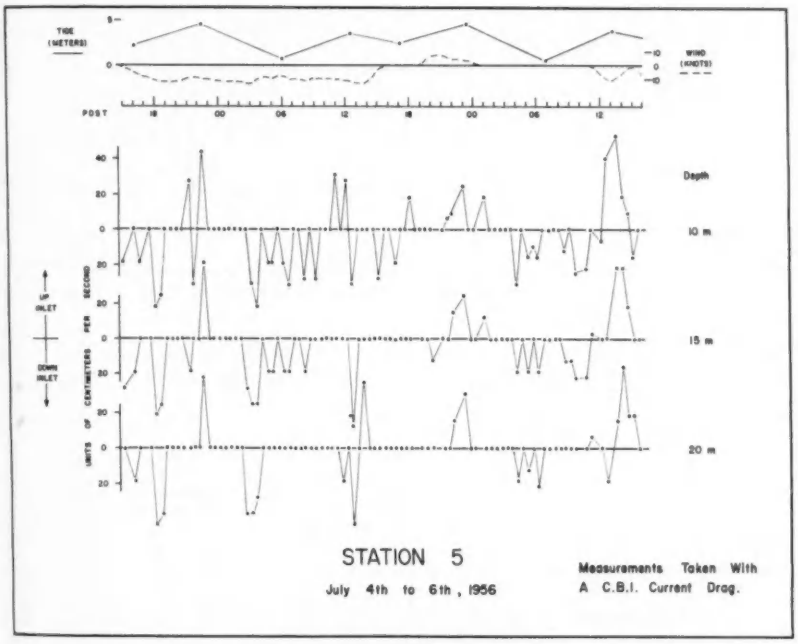

FIG. 14b. Longitudinal components of currents at 10, 15 and 20 m depth at Station 5, Knight Inlet, 4–6 July, 1956.

The current range at the 2-m depth was larger than at other depths. At 4 and 6 m the range was about 75% of that at 2 m. At 10, 15 and 20 m it was 50% of the range at 2 m. The current range at greater depths was only 25% of that at 2 m.

Inspection of the series of hourly profiles of the longitudinal components (Fig. 15) reveals some interesting features. The flood current appeared to start at the depths of 50 or 100 m and then spread downward. This early flood usually

started after predicted high water and would not extend to 300 m until predicted low water.

The profiles given by 25-hour means for the first and last 25 hours are shown in Fig. 16. The first profile corresponds to a period when there was an average down-inlet wind of 10 knots. The second period was one of little wind.

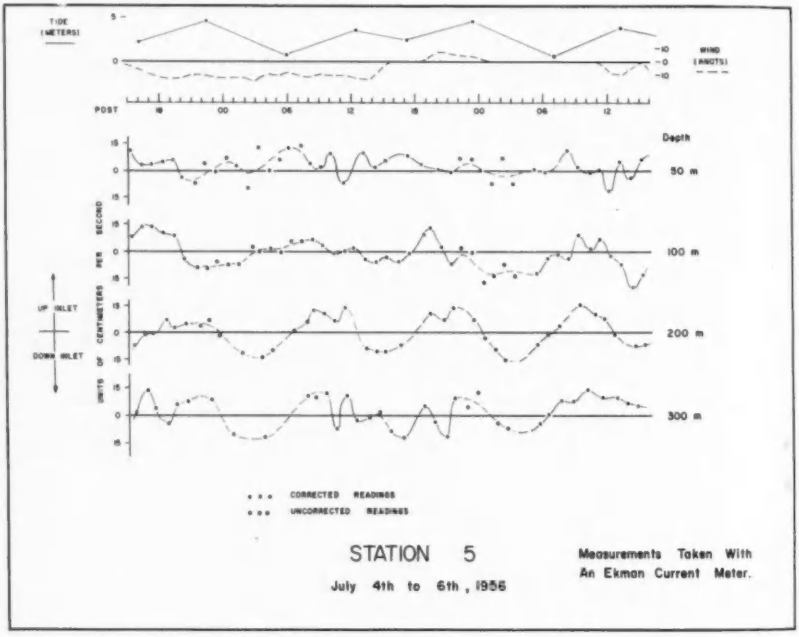

FIG. 14c. Longitudinal components of currents at 50 to 300 m depth at Station 5, Knight Inlet, 4–6 July, 1956.

The first profile shows net currents at 100, 200 and 300 m which were barely significant. An up-inlet flow took place at 50 m. There was a net flow down-inlet at all depths to 20 m with a particularly strong flow down-inlet from the surface to 5 m. There was a significant minimum in the down-inlet flow at 10 m, or alternatively, a maximum at 15 m.

The final period of 25 hours showed several changes. Net down-inlet currents from the surface to 20 m were reduced. The minimum in the down-inlet flow observed at 10 m in the first 25 hours had disappeared. The up-inlet flow, evident only at 50 m during the first 25 hours, showed also at 15 and 20 m in the last

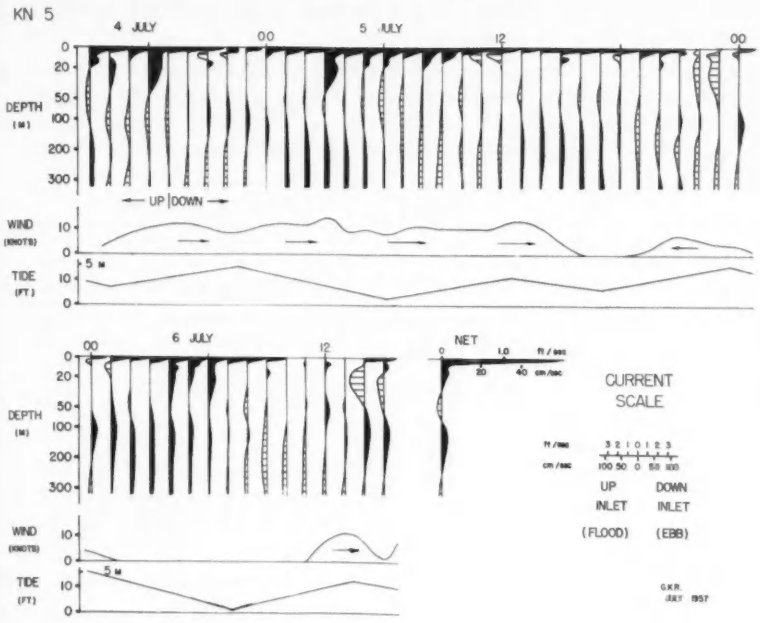

FIG. 15. Hourly profiles of longitudinal components of currents at Station 5, Knight Inlet, 4–6 July, 1956.

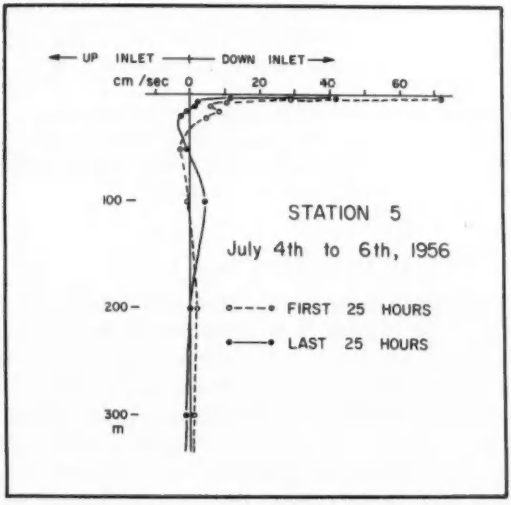

FIG. 16. Net current profiles over first and last 25 hours at Station 5, Knight Inlet, 4–6 July, 1956.

25 hours. Net currents at 200 and 300 m were again small, but at 100 m there appeared a significant net current down-inlet.

The transverse components at 50, 100, 200 and 300 m (Fig. 17) were of the same magnitude as the longitudinal components at the same depth but irregular in direction.

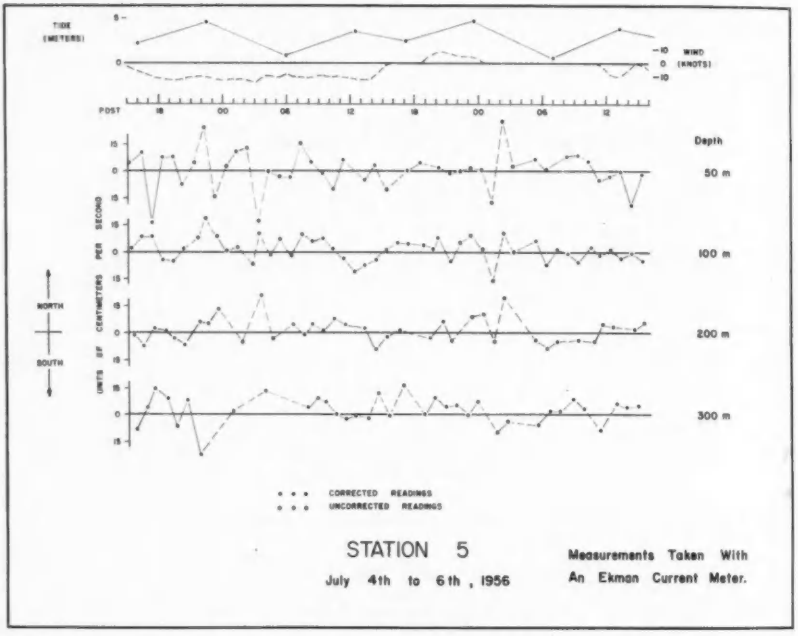

FIG. 17. Transverse components of currents at 50 to 300 m depth at Station 5, Knight Inlet, 4–6 July, 1956.

(3) STATION 5, JULY 8 TO 11, 1956

The time series plot of the longitudinal component of currents (Fig. 18a, 18b and 18c) shows the oscillating currents observed at the other stations. The currents at 50 m and below were very like those measured during the first anchorage with a somewhat greater range. The oscillations were more coherent in the second half of the period than in the first. Again the currents at 100 m were slightly less coherent than at 200 and 300 m. Currents at 50 m were more coherent than during the first anchorage. Currents at 200 and 300 m were those one might deduce from the predicted tide, both in magnitude and phase; that is, up-inlet flow from predicted low water to high water and down-inlet flow from predicted high water

to low water. The magnitude was in reasonable agreement with that calculated from the tidal prism, tide rise and the cross-section at the station assuming that the tidal flow was uniform over the whole section.

Before considering the currents in the upper 20 m, the wind conditions should be indicated. During this complete period there was an up-inlet wind, with the diurnal cycle to maximum speeds of 25 knots. Along with this change in wind

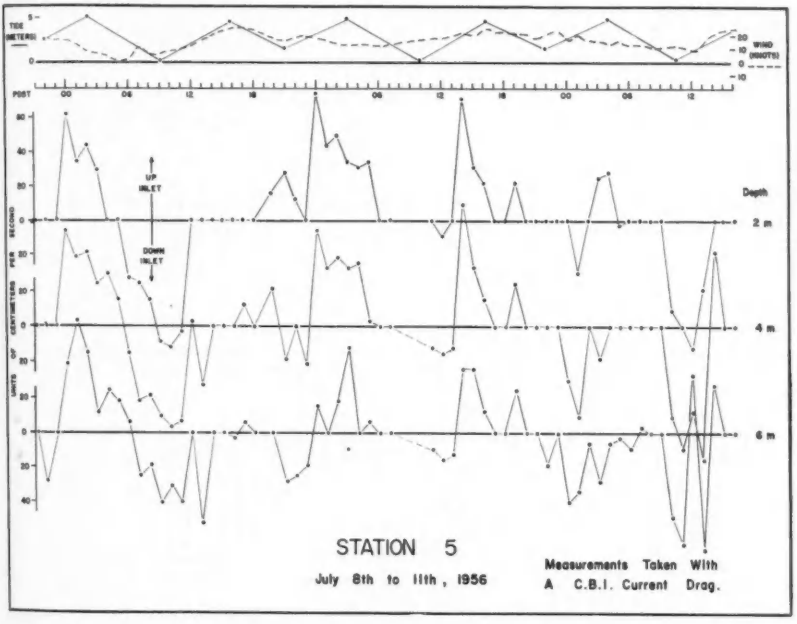

FIG. 18a. Longitudinal components of currents at 2, 4 and 6 m depth at Station 5, Knight Inlet, 8–11 July, 1956.

conditions from the first anchorage there was a change in the character of the currents in the upper 20 m. The oscillations were more nearly symmetrical about the mean current than before (compare Fig. 18a and 14a). The mean current also reversed during about 24 hours in the middle of the period. The oscillations were not those one might expect from the predicted tide. The magnitude was too great and there was a 90° phase lag.

The range of current in the longitudinal direction varied with depth. If the range at 2 m is taken as 100%, then at 4 m it was 100%, at 6 m 90%, at 10 m 75%, at 15 and 20 m it was 50%, and about 25% at 50 m and deeper.

The hourly profiles (Fig. 19) of the longitudinal component present a fairly consistent pattern for the first half of the period. Any time during the 3 hours before predicted high water there appeared a strong up-inlet current from the surface to 20 m. The water at 200 and 300 m was in the last stage of up-inlet flow when this surface flow began. At the same time as this up-inlet flow took place at the surface there occurred a down-inlet current at 50 and 100 m. As the predicted tide passed high water the down-inlet current spread to the 200- and

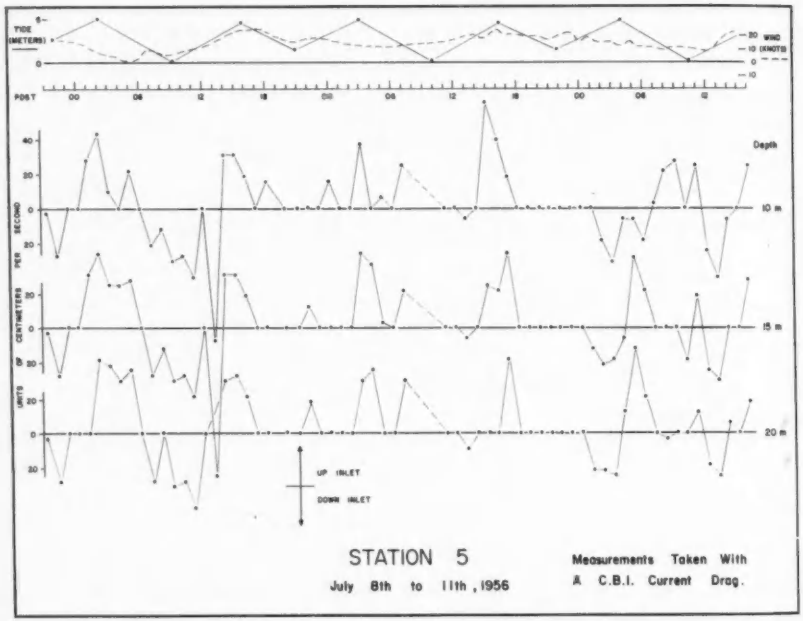

FIG. 18b. Longitudinal components of currents at 10, 15 and 20 m depth at Station 5, Knight Inlet, 8–11 July, 1956.

300-m depths and the surface up-inlet flow deepened to about 50 m. Midway between high and low water surface up-inlet flow stopped or reversed to a small down-inlet flow so that for the remainder of the predicted ebb the whole column was moving down the inlet. There was a fairly consistent flow for the remainder of the predicted ebb at depths of 50 m and more. During this last period, though, the surface down-inlet currents had speeds from zero to 75 cm/sec.

During the second half of the period the flow at 50 m and deeper followed the above pattern, but in the surface 20 m the flow was different. The up-inlet flow was later and at a greater depth. It also persisted into the second half of the predicted ebb.

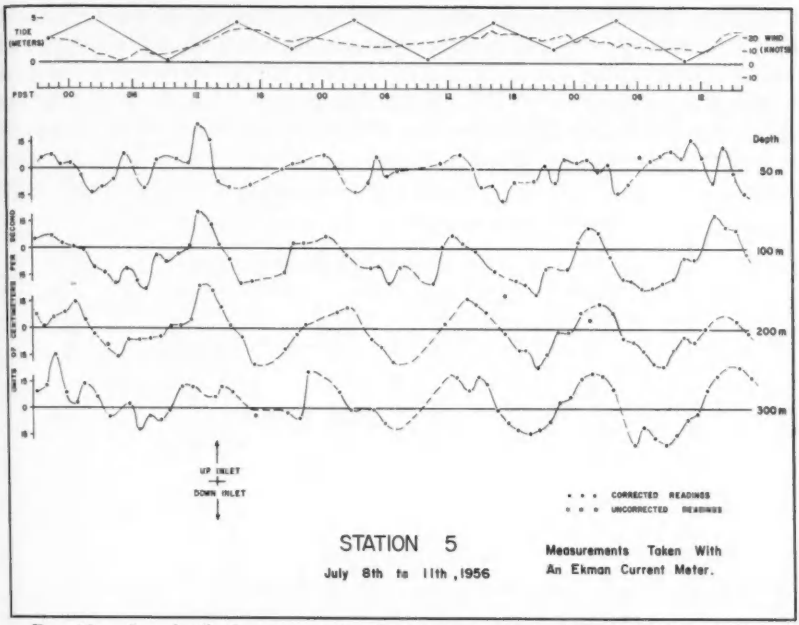

FIG. 18c. Longitudinal components of currents at 50 to 300 m depth at Station 5, Knight Inlet, 8–11 July, 1956.

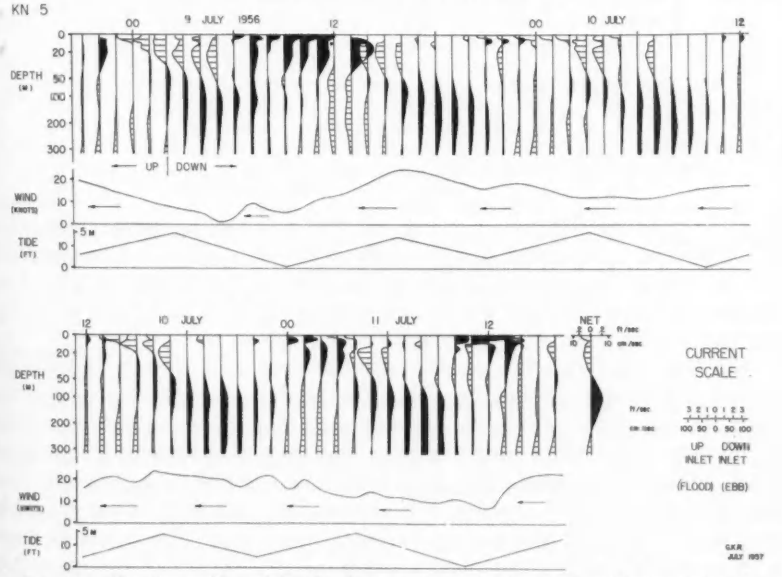

FIG. 19. Hourly profiles of longitudinal component of current at Station 5, Knight Inlet, 8–11 July, 1956.

Three 25-hour means are plotted in Fig. 20. These cover the first, middle and last 25-hour periods. Since there were only 68 hours of observation there is some overlap of data in these means. In all three profiles there was a significant up-inlet flow at a depth of 300 m. At 200 m a net down-inlet flow became significant in the middle and last profiles. At 100 m there was a marked down-inlet

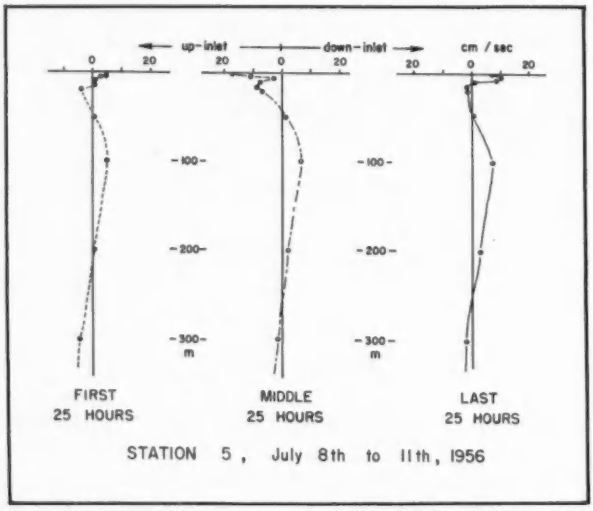

FIG. 20. Net current profiles over first, middle and last 25 hours at Station 5, Knight Inlet, 8–11 July, 1956.

flow in all three profiles. At 50 m the net flow was not significant. Somewhere between 50 and 20 m there was a "depth of no net motion". It was probably closer to 50 m. The upper boundary of the up-inlet flow cannot be placed too accurately as it appears that the wind had a direct effect on flow down to perhaps 15 m, thus penetrating to the region of this boundary.

The first 25 hours was a period with a mean up-inlet wind of 14 knots and there was still a net down-inlet flow from 2 to 15 m though the flow at 20 m was up-inlet. In the middle profile the average wind had increased slightly and had been blowing for a longer period of time. The flow in the upper 20 m was all up-inlet although there appeared to be two flows separated by a minimum up-inlet flow at 6 m. During the last period it is seen that the surface flow was down-inlet despite a continuing average wind of 16 knots up the inlet. The maximum down-inlet flow in this last profile was at 4 and 6 m rather than close to the surface (2 m) as was noted in the net currents of the first 25 hours.

The transverse component at depths of 50, 100, 200 and 300 m (Fig. 21) was irregular with possibly a larger amplitude at 50 m than at the greater depths. In contrast to the first period of measurements the amplitude of fluctuations of the transverse (cross-inlet) component was one-half or less that of the longitudinal component. This difference between the two periods of observation may be due to the fact that a greater percentage of measurements for the second period had observations available to permit correction for ship motion.

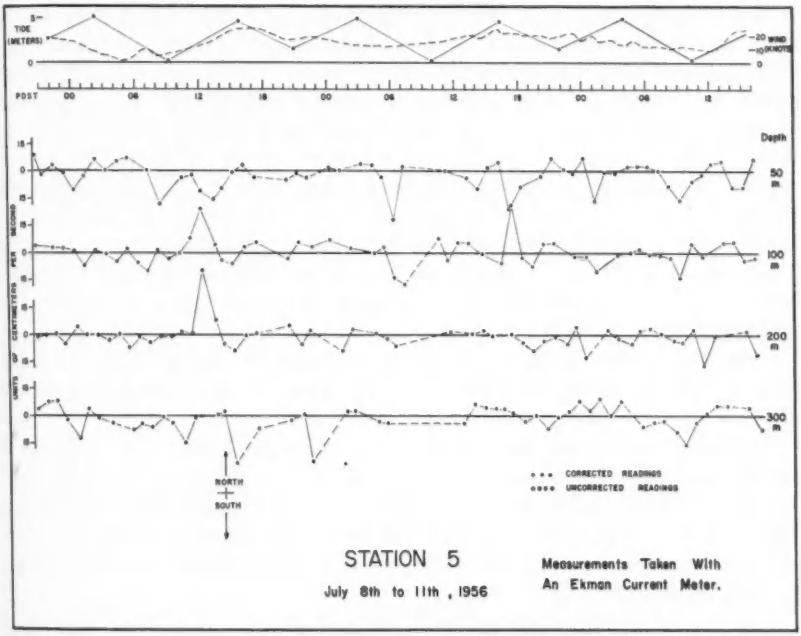

FIG. 21. Transverse components of currents at 50 to 300 m depth, Station 5, Knight Inlet, 8–11 July, 1956.

DISCUSSION

SHIP MOTION

In previous trials it had been recognized that ship motion might contribute a large proportion of the current meter reading. The 1956 data bear this out — especially for the deep station, Knight 5.

If the mean speed for ship motion is compared with the maximum half-range of currents measured at each station, some idea of its importance can be determined. For Sta. 5 the mean ship speed during current measurements was 7.5 cm/sec compared with a half range in current of 15 cm/sec. Here, then, the mean ship speed was 50% of the maximum currents measured. Clearly a correction must be

made and made accurately. In the case of Sta. 3½ more favourable conditions existed which put the mean ship speed at only 4.5 cm/sec compared with a half range in currents of about 70 cm/sec. The ship speed, therefore, averaged only 7% of the current speed.

These two comparisons suggest three comments. First, the Ekman current meter readings at Sta. 3½ are little affected by ship motion. Therefore the accuracy of determination of the ship movement is not so critical. Also, data taken at this station in previous years can be used with confidence even when the ship movement was not determined. Secondly, currents indicated by the Ekman meter on Sta. 5 must be viewed critically. When it is noted that only 69% of Ekman measurements were corrected for ship movement for the first anchorage on Sta. 5 compared with 99% on the second anchorage, it is clear that the data for the second anchorage are more reliable. Thirdly, as mentioned in the preceding paragraph, the ship movement at Sta. 5 constitutes a large proportion of the Ekman meter readings. Therefore the accuracy of the currents obtained by correcting the Ekman readings is largely determined by the accuracy with which the ship movement is known. The accuracy of the ship velocity calculation is less than the Ekman current meter accuracy. In particular, the cross-stream components of currents at Sta. 5 are in greater doubt than the longitudinal components. For this reason, limited significance was attached to individual values or means of the cross-inlet component at Sta. 5.

For the reason just stated it seems advisable to attempt to improve the technique of determining the ship movement when anchored at stations such as Sta. 5.

As mentioned in the description of the instruments, the C.B.I. drag affords a simple and rapid means for determining the current profile in the upper layer. The depth to which it may be used is limited by the increasing proportion of wire drag to biplane drag. The Ekman current meter may be used at any depth, but the direction indication may be influenced by magnetic effects from the ship at less than about 20 m.

At Sta. 3½ both instruments were used at 10 and 20 m in order to compare them. The measurements were not made simultaneously but in the regular schedule of operations as outlined in the procedure. That is, a current profile to 20 m was taken every half hour with the C.B.I. drag, and the Ekman meter was used at 10 and 20 m shortly after the C.B.I. drag current profile taken on the hour. Any comparison must therefore be statistical rather than by direct comparison of readings.

The plot of both Ekman and C.B.I. drag measurements (the along-inlet component) are shown in Fig. 22. In general, the peak currents indicated by the Ekman meter were less than those indicated by the drag. Since the current in the upper 20 m is usually unidirectional, it appears that drag on the wire is not negligible. The difference between the Ekman meter and C.B.I. drag was in a direction indicated by that of the mean flow above the particular depth at which measurements were compared. The wire on which the C.B.I. drag was suspended was in this flow above the depth of measurement and there was drag on the wire

due to this flow. If this drag on the wire was significant then the C.B.I. drag measurement means would deviate from the true average in the direction of the mean flow above the depth of measurement. This, in fact, is the direction in which the means of the C.B.I. drag measurements deviate from those of the Ekman meter measurements. A correction for this wire drag can be applied to the C.B.I. drag measurements.

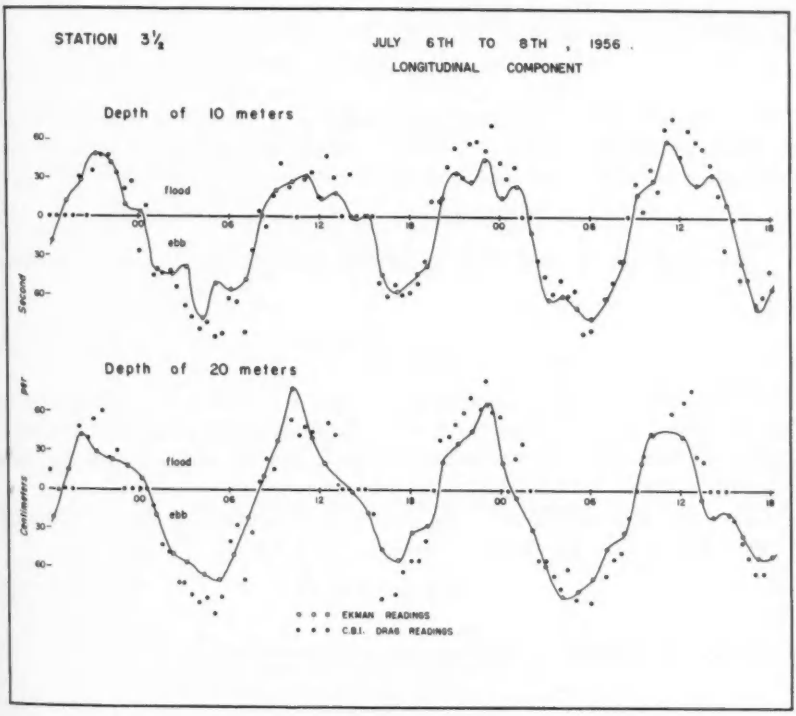

FIG. 22. Comparison of Ekman current meter and C.B.I. current drag readings at Station 3½, Knight Inlet, 6–8 July, 1956.

A formula directly relating the current at one depth to the angle measured at the surface cannot be simply stated if the drag on the wire is significant. This is because the drag on the wire depends on the strength of the current between the surface and the depth of measurement.

The currents given by the equation developed by Burt and Pritchard (1951) were first plotted for each profile, then a non-uniform grid of rectangles based on an equation developed below provided a correction to the square of the velocity given by the simplified equation deduced by Burt and Pritchard. This correction

was applied every 5 m to correct the profile successively in 5-m intervals from the surface down to 20 m.

The development of the formula on which the grid was constructed is outlined below. First, the equation developed by Burt and Pritchard is reviewed. Referring to the force diagram in Fig. 5:

$$\tan\ \theta = \frac{F}{W} \tag{1}$$

where F is the drag force on the biplane, W is the weight of the drag in water and θ is the wire angle measured at the surface. Now,

$$2F = C_p A \rho v^2 \tag{2}$$

where C_p is the drag coefficient of the biplane, A is the area of the biplane, ρ is the density of the fluid and v is the actual velocity at the depth of measurement. Hence the velocity, V, given by considering the drag on the biplane only, is

$$V = (2W/C_p A \rho)^{1/2}\ (\tan \theta)^{1/2}. \tag{3}$$

In considering the drag force on the wire, there is added to F another force N, given by

$$2N = C_w \rho d \int_0^h v_z^2 \,.\, \mathrm{d}z \tag{4}$$

where N is the force due to the drag on the wire, C_w is the drag coefficient of the wire, d is the diameter of the wire, h is the depth of measurement and z is depth measured downward from the surface. Only the vertical projection of the wire, perpendicular to the current, is considered here.

Then the angle measured at the surface is determined by the balance of T, W, and F plus N (Fig. 5). Hence:

$$\tan\ \theta = \frac{F + N}{W}. \tag{5}$$

Substitution of equations (2) and (4) into equation (5) produces

$$\tan \theta = \frac{C_p A \rho v^2}{2W} + \frac{C_w \rho d}{2W} \int_0^h v_z^2 \,.\, \mathrm{d}z\,. \tag{6}$$

Now θ was the angle measured and is related to V by equation (3). Hence

$$\frac{C_p A \rho V^2}{2W} = \frac{1}{2W}\left(C_p A \rho v^2 + C_w \rho d \int_0^h v_z^2 \,.\, \mathrm{d}z\right)$$

and therefore

$$V^2 - v^2 = \frac{C_w d}{C_p A} \int_0^h v_z^2 \,.\, \mathrm{d}z\,. \tag{7}$$

This equation provides the correction. The drag coefficient for the $\frac{3}{32}$-inch stranded steel wire used is not precisely known. However, it is known that for

currents of the magnitude measured the drag coefficient for a smooth cylinder is between 1.0 and 1.1. The fact that the steel wire was stranded and therefore rougher may indicate a slightly higher drag coefficient. Lacking exact measurements, the value was taken as 1.2 for the purpose of calculations. This is the same value as that used for the biplane.

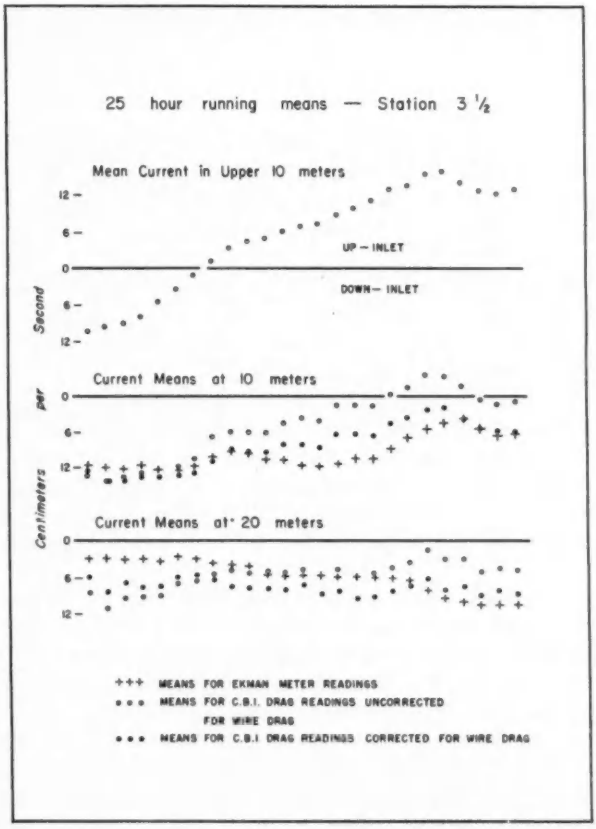
25 hour running means — Station 3 ½
Mean Current in Upper 10 meters
12
6
0
6
12
UP — INLET
DOWN — INLET
Centimeters per Second
Current Means at 10 meters
Current Means at 20 meters
+++ MEANS FOR EKMAN METER READINGS
• • • MEANS FOR C.B.I. DRAG READINGS UNCORRECTED FOR WIRE DRAG
• • • MEANS FOR C.B.I. DRAG READINGS CORRECTED FOR WIRE DRAG

FIG. 23. Illustration of the effect of applying correction for drag on suspension wire of C.B.I. current drag.

The correction was carried out for the C.B.I. drag measurements, with the results shown in Fig. 23. There still remains some discrepancy between the Ekman averages and the corrected C.B.I. averages, though agreement is considerably improved. Other errors can possibly account for these discrepancies.

Lift on the wire has also been neglected. It has a tendency to oppose the weight W. An estimate of this error can be made by considering an average angle

measurement of 30° for measurements at Sta. 3½. Assuming a uniform velocity from the surface to the depth of measurement the lift is found to be about 7% of the weight of the drag, contributing a possible velocity error about 3% too high for the C.B.I. drag. In addition, the Ekman meter used has been checked in the surface layers against a Price–Gurley current meter with agreement to within 15% between the two instruments.

Currents

(1) Station 3½

Currents at all depths at Sta. 3½ showed a long-period oscillating component superimposed on a mean flow. These oscillating currents were of the same range at all the depths of measurement near the bottom. The oscillating components showed peaks at times midway between predicted high and low water and showed slack water or zero current near times of predicted high and low water. These facts are strong evidence that flow at the sill region is typical tidal channel flow and that the oscillating currents are due primarily to the rise and fall of the tide in the inlet. Further evidence for this last statement will be presented below in the discussion of transport through the section.

The general characteristics of the mean flow on which the oscillating currents were superimposed did not remain the same throughout the period of observation. As Fig. 13 shows, the original two-layer mean flow, out in the upper layer and in below, changed during the second period to a three-layer flow. In this, the up-inlet surface flow is attributed directly to the frictional stress of the wind, and the increased outward flow between 8 and 60 m is a consequence necessary for continuity.

It should be noted that the depth of outflow is apparently well below the halocline, which is not deeper than 15 to 20 m in this part of the inlet. The depth of no net motion (for the no wind condition) would appear from Fig. 13 to be at about 45 m if the point at 40 m is really significant. However it is doubtful if this is the case and a small up-inlet instead of down-inlet value here would shift the depth of no net motion to 25–30 m, much closer to the halocline.

Topography may also influence the flow in this region. The discussion so far has dealt with only the along-inlet components of the current. However, there are large cross-inlet components of the current which, when averaged, indicate a net flow towards the side of the inlet. The best demonstration of this feature is in the mean directions of the flood and ebb at the depths of 10, 20, 40, 60 and 70 m (see Table II). The current directions on flood and ebb did not differ by 180°. Ebb directions at all depths lay between 271° and 286° true. At 10 m on the flood it was very close to 104° (i.e. differed by 180°) but at 20 and 40 m it was 125° and at 60 and 70 m it was about 135° true. There is an increasing southward set of the flood current as the depth increases. The slight northward set of the ebb currents was consistent with the southern shoreline of the inlet from the east to Prominent Point (Fig. 4).

The topography may explain the southward set of the flood currents and possibly its variation with depth. The axis of the outer basin is inclined to the axis of the inner basin. A current flowing up-inlet in the outer basin region is partially trapped in the shallow of Hoeya Sound and Lull Bay (Fig. 4). Water escaping from this region must flow around Boulder Point with a southward component. This would deflect the flood currents to the south.

There was a big difference between flood current directions in the first and last 25 hours at depths of 20 and 40 m. At 20 m it changed to 103° from 125° true. Thus it was aligned parallel to the current direction at 10 m in the last 25 hours. This could possibly be an indication that the wind stress at the surface has a direct influence to a depth of 20 m. The change in the magnitude of the mean current between the first and last 25 hours indicated a nearly significant change in the direction opposite to that of the wind stress, which would seem to contradict the above statement. However, the mean current applies to a complete tidal cycle, while the angles were calculated only from either the flood or ebb current velocities. It is possible that as a consequence of changes in density distribution the wind stress could penetrate deeper during currents which were parallel to it (flood in this case) than during currents which opposed it.

At 40 m the change in the flow is marked in the direction of the flood current as well as in the increase in magnitude of the mean flow down the inlet. Both of these appear to be due to only one phenomenon, a decrease in magnitude of the longitudinal component of the current on the flood.

(2) Station 5

As at Sta. 3½, the currents could be resolved into an oscillating current superimposed upon a mean current. At this station, however, the currents at 50, 100, 200 and 300 m were only one quarter of the magnitude at 2 m. The currents at different depths did not occur with the same phase. In general there appear to have been two regions, surface and deep, separated by a broad boundary region from 20 to 100 m. The confused nature of currents at 50 m may be due to the fact that this depth is in this transition region. As noted in the description, the currents at 50 m were of the same magnitude as those at greater depths, but did not show any systematic oscillating component.

The deeper region will be dealt with first. At 300 and 200 m and to a lesser degree at 100 m the currents were oscillatory and superimposed on a very small net current. The slack water coincided with predicted high and low water, suggesting that these currents were caused by tidal forces. Further support for this idea is found in the magnitude of the oscillating currents. These magnitudes are in agreement with tidal currents calculated assuming lateral uniformity and uniformity with depth for tidal flow to fill or empty the inlet according to the predicted tide heights.

In the surface layer there was found to be an oscillating current, but at 2 and 4 m the current had a range four times larger than the tidal currents calculated as above. The range in the oscillating currents decreased with depth. These oscillations were not in phase with movements at depth, but did occur in a

systematic fashion related to the predicted tide heights. Whatever mechanism or mechanisms were present to cause the flow in the surface layer, there was certainly a strong component with a tidal period.

The vertical profiles of the net currents show three consistent features that are distributed in depth and may be related to the two flow regimes of oscillatory currents: (a) Starting at the surface there was an outflow except when a strong up-inlet wind was blowing; (b) there was inflow below this surface layer extending to below 50 m; and (c) at 100 m there was a down-inlet flow that slowly but steadily increased over the course of the week of measurements.

The outflow (a) and inflow (b) have an explanation as described in the Introduction. The runoff must escape in the surface layer and the return (up-inlet) flow of salt water below this apparently extends to about 50 m. The average transport for the two periods of current measurements for depths down to 50 m was distributed as follows:

Fresh water in the upper 10 m	—	600 m^3/sec, down-inlet
Salt* water in the upper 10 m	—	1700 m^3/sec, down-inlet
Salt* water at 10 to 50 m	—	1200 m^3/sec, up-inlet.

No explanation is offered for the well developed down-inlet flow (c) observed at 100 m. It can only be pointed out that this flow was correlated with a complete change in the wind stress at the surface, from down-inlet to up-inlet. There was also a correlation with the transition from neap to spring tides.

(3) Tides and tidal currents

No tidal stations were set up in conjunction with these current measurements. For this reason currents have been related to the predicted tide at Alert Bay. Comparison of the actual tide record at Alert Bay with the predicted tides shows excellent agreement.

Previous studies in the British Columbia inlets have shown virtually no time lead or lag in the tidal rise along the whole length of an inlet, though there may be a difference in the tidal range (Dawson, 1920). These studies are reflected in the present Tide Tables which give no time difference between Alert Bay and Glendale Cove (see Fig. 1) and a mean ratio of rise of 1.15 for high tides. For these reasons it is felt that any current that is primarily tidal in character will be directly related to the rise and fall of the tide as predicted. This was the case at all depths of measurement at Sta. 3½ and at the greater depths at Sta. 5. A significant result of the present experiments was the discovery of tidal currents in the inner basin well below the depth of the inner sill (67 m).

The currents at Sta. 5 in the 20-m surface layer were fairly uniformly out of phase with the calculated tidal currents. Previous estimates have been made of the depth of tidal influence by only considering the amplitude of currents at

*Salinity taken as mean value 10–50 m in both cases. The last figure is uncertain because of the necessity to interpolate between 20 and 50 m and the lack of salt balance may or may not be real.

the surface (Trites, 1955). The present data suggest that this is not a valid procedure at such stations as Knight 5.

There is the question of whether tidal currents should be expected to be a smooth function of time. A check was made of the slopes of the actual tide records at Alert Bay for this period of observations. The shortest time interval over which a slope could be accurately obtained was 10 minutes and even with this 10-minute slope it was evident that tidal currents were not smooth functions of time and certainly did not adhere to a sinusoidal curve. Peaks tend to be flattened and "slack water" was a period of sharp current bursts. The data show this clearly, especially the data taken half-hourly with the C.B.I. drag (see Fig. 10a, 14a, 14b).

(4) Wind effects

There were long periods of wind during all three anchorages. It is obvious from the vertical profiles of net currents that the wind stress had a large direct effect on the surface currents. The flow of water at the surface was accelerated or impeded — even reversed — during the period of these observations. Reversal of the surface current is shown by comparing the first and last 25 hours on Sta. 3½ (Fig. 13) and the first and middle 25 hours of the second anchorage on Sta. 5 (Fig. 20). The acceleration of near-surface flow is clearly shown in the period of down-inlet wind (first 25 hours) on the first anchorage at Sta. 5 (Fig. 16).

A comparison of the net currents at the surface in the middle and last profiles for the second anchorage at Sta. 5 indicates that the wind stress can only reverse surface flow for a limited time. Apparently between these two periods the flow near the surface has returned to the down-inlet direction despite the fact that a strong up-inlet wind was still blowing. It appears that a pressure gradient built up within 30 hours to balance the wind stress due to an average wind of 16 knots.

The data suggest that the depth of direct influence of the wind can be quite variable. When the magnitudes of mean currents are considered, it is found that the wind appears to have had direct influence down to only 6 m at Sta. 3½. Current direction data at the same station suggest that this direct effect may have penetrated to 20 m, but the change in magnitude of mean current at this depth, if significant, was in the opposite direction to the wind stress. Since the direction data were obtained by considering flood and ebb currents separately and the mean currents in a 25-hour period, the apparent contradiction may not exist. It seems possible that the wind stress could have had an influence to a greater depth on the flood than on the ebb. This could be due to a change in the water structure (density gradients) with the state of the tide. Turning to data from Sta. 5, there are seen to be large direct effects down to at least 20 m. The reason for the difference between Sta. 3½ and 5 is probably associated with the difference in water structure at the two stations.

There is evidence for indirect effects of the wind stress. Some flows, such as those at 40 m on Sta. 3½ and at 100 m on Sta. 5, underwent changes that were correlated with changes in the wind stress at the water surface. The change in the

flood flow at 40 m on Sta. 3½ is thought to be strong evidence for indirect influence of the wind. The flow at 100 m on Sta. 5 is not considered to be as strong evidence for this phenomenon. If flows at these depths were influenced by the wind, it appears that the flows were of a compensatory nature. That is, they changed in the direction opposite to that of the change in the wind.

(5) HOURLY TRANSPORTS

The hourly current profiles obtained were used to calculate a transport through the inlet cross-sections at the stations, making the assumption of lateral uniformity as done when calculating tidal currents. A table method was used to calculate the transport from the currents at the particular depths. Linear interpolation between observed currents is implied in this method.

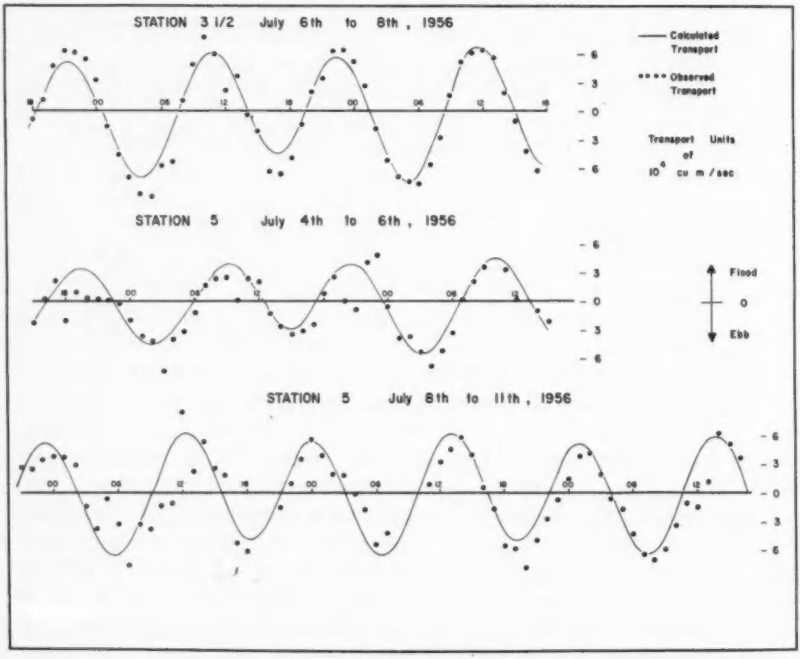
STATION 3 1/2 July 6th to 8th, 1956
Calculated Transport
Observed Transport
Transport Units of 10^6 cu m / sec
STATION 5 July 4th to 6th, 1956
Flood
Ebb
STATION 5 July 8th to 11th, 1956

FIG. 24. Volume transports calculated from tidal rise and fall, and from current profiles.

The results for all three anchorages are shown in Fig. 24. The solid line denotes the transport calculated from the predicted tide heights, the tidal prism, and the assumption that the tidal current was uniform across the section and that it varied sinusoidally.

For Sta. 3½ there was a fairly close correspondence between calculated and observed transports. This is interpreted as a reasonable assurance that currents near mid-channel at that station are representative of the total cross-section. The

irregularities that showed in the currents at individual depths are smoothed out when averaging over the whole water column.

The transports at Sta. 5 show greater divergences from the calculated curve. Periods of flood and ebb can be recognized, but the variation is not sinusoidal and shows large fluctuations. This is taken as evidence that flow across the section is not laterally uniform.

There has been some further evidence for both lateral uniformity and lateral non-uniformity in surface currents. Experiments with photography of lines of dye deposited across inlets (Pickard, 1953) have shown a full range of conditions. Some results show a fairly uniform flow across the inlet with the exception of regions close to shore. In other instances, small localized jets have appeared. The latter could complicate transport calculations based on current measurements taken at a single position in the inlet. In general the currents near mid-inlet are greater than at the sides.

If current measurements are taken in one position in the inlet there is considerable doubt whether they will be representative of currents to either side of that position. It has been noted that there were large lateral movements of the ship, encompassing about one-quarter of the width of the inlet, during the second anchorage on Sta. 5. It is therefore possible that the ship was moving in and out of current patterns. The attendant complications in the interpretation of current measurements are obvious.

(6) Fresh water transport

An estimate has been made of the fresh water transport in the surface layer from the net currents and the salinity of this layer. Data from both stations were used. Seven 25-hour periods were chosen representing the entire duration of the current measurements with as little time overlap as possible. It was found that the mean fresh water transport was 310 m^3/sec down-inlet although it varied from 2000 m^3/sec down-inlet to 1000 m^3/sec up-inlet depending on the duration and direction of the wind.

It is possible that this is an underestimate of the net fresh water transport, because the salinity profiles on which it is based were those taken after the wind had been blowing up-inlet for some time and the usual consequence of this is to bring in more saline water than in the no wind case.

This net fresh water transport should represent approximately the river flow into the inlet unless there is a deepening of the brackish surface layer.

Estimates of the mean monthly transport of fresh water into the inlet have been made (Pickard and Trites, 1957) on the basis of precipitation and watershed data. The values are:

June: 27.8×10^3 ft^3/sec (790 m^3/sec)
July: 21.7×10^3 ft^3/sec (615 m^3/sec).

It is to be noted that these are mean monthly values, and daily or weekly values could differ appreciably from these. It is felt that the value of 310 m^3/sec obtained (being probably an underestimate as explained) is in reasonable agreement with these figures.

If the net surface layer, and therefore fresh water, transport is up-inlet there must be a deepening of the brackish layer and storage of fresh water from the continuing river runoff. Unfortunately, no data on the fresh water storage are available but that this is limited is already evident from the fact that the down-inlet surface flow is only held back for a limited time by the wind stress.

(7) Net transport

The only long-term net transport to be expected through any complete section of the inlet is the fresh water component of the surface layer. As noted in the previous section, this averaged about 300 or more m^3/sec down-inlet when calculated as the fresh water component of the surface layer. The net transport through the whole column should just equal this 300 m^3/sec with the transports of salt water at various depths cancelling each other.

Under the assumptions made in the transport calculations it was found that the net transport did not equal the fresh water component of the surface layer transport. At both stations there was calculated a down-inlet transport in every 25-hour period. At Sta. 3½ it was 3,700 m^3/sec and at Sta. 5 it was 8,500 m^3/sec. The net transport is in the right direction, but is an order of magnitude greater than the fresh water transport.

If these values were correct, the water level in the inlet would have fallen at the rate of 1 to 2.5 m per day. However, it has already been remarked that the assumptions under which these transports were calculated are in doubt.

There is the question of just how significant this net transport was in terms of the accuracy of measurements and the assumptions made in the calculations. It should be noted that despite the fact that the net transport estimated above is of the order of ten times the fresh water transport, this estimated net transport itself is still only one tenth of the average transport required to fill or empty the tidal prism during a flood or ebb. It corresponds to a mean current over the whole cross section at Sta. 3½ of 3 to 6 cm/sec, and at Sta. 5 of 0.5 to 1 cm/sec.

Nonetheless, the net transport calculated was always in one direction and does require discussion. Realizing that it was based on currents measured in mid-channel, possible explanations for this apparent net transport are suggested: (1) It may have been that the ebb flowed preferentially in mid-channel, and the flood at the sides. (2) There may also have been a horizontal closed circulation with its down-inlet portion in mid-channel. (3) The smooth interpolation between the rather widely spaced points in the net water current profile may have been unjustified. (4) The mean velocities may have been significantly smaller than the measured values at mid-channel. (5) it may have been an artifact associated with the presence of internal waves.

It should be noted that the discrepancy appears to exist in the deeper water; the fresh water transport calculations indicate reasonable transports in the upper layer.

At Sta. 5, it is seen that the net flow developed at the 100-m depth is sufficient to account for the net down-inlet transport. If the cause for this flow could be determined, the problem might be solved.

(8) Internal waves

One feature of the inlets which has been noted on several occasions is the existence of internal waves or waves at density variations in the water structure. These are certainly present in the upper layers in the region of the large density gradients there, and have been observed by serial temperature observations and by their surface manifestations (alternate slick and ruffled bands) (Pickard, 1954). They are frequently observed in Knight Inlet in the region between Sta. 3 and 5.

There is also evidence to suggest that internal waves are also present at greater depths in this and other inlets. During this set of current measurements, BT casts were made regularly to a depth of 270 m at Sta. 5. From these it appears that isotherms oscillated vertically with a tidal period. In particular there was a temperature minimum which oscillated between the 75- and 150-m depths. (The minimum is thought to be the residue of severe winter cooling.) This series of bathythermograms is, at present, the subject of a separate study. The oscillation of these isotherms may be due to internal waves.

The existence of internal waves may explain one feature of the net current profiles. This feature is present in the mean current profiles for the first 25 hours on Sta. 3½ and for the first 25 hours on Sta. 5 (first anchorage) which are shown in Fig. 13 and 16. In the surface layer at Sta. 3½ there was a minimum at 4 m and a maximum at 15 m in the down-inlet flow. At Sta. 5 the minimum was at 10 m and the maximum at 15 m. This feature has been noted before in current measurements taken at Sta. 4 in Knight Inlet (Trites, 1955). This pattern of a minimum and maximum can be regarded as either a minimum alone, a maximum alone, or both a minimum and maximum superimposed on a net current which monotonically decreases with depth. For the present data there is no way of differentiating between these possible interpretations.

A simplified picture of an internal wave will demonstrate the possible effects of internal waves on current measurements. In the first instance, for progressive internal waves of finite amplitude there is a small transport of fluid in the direction in which the wave travels. The second effect is an *apparent* net flow in the direction of wave travel when current measurements are taken at a depth between the crest and trough of an internal wave which persists over any great percentage of the time.

The second effect is the one considered here. In Fig. 25 is shown an internal wave at a density discontinuity. It can be seen that measurements taken continuously at level A will show an apparent net flow in the direction in which the wave is travelling. It must be emphasized that this is just a simple presentation. The effect of a density gradient (which is the usual case in an inlet) rather than a sharp density discontinuity, is to yield a more complex situation in which several modes of oscillation are possible.

Applying this to the net current profile, and in particular to the minimum and maximum near the surface, it seems possible that these may be due to internal waves in the boundary between the brackish surface layer and the denser sea water below. The fact that strong internal waves in the inlet are often observed (by the slick and ruffled bands) to have been moving up the inlet suggests that

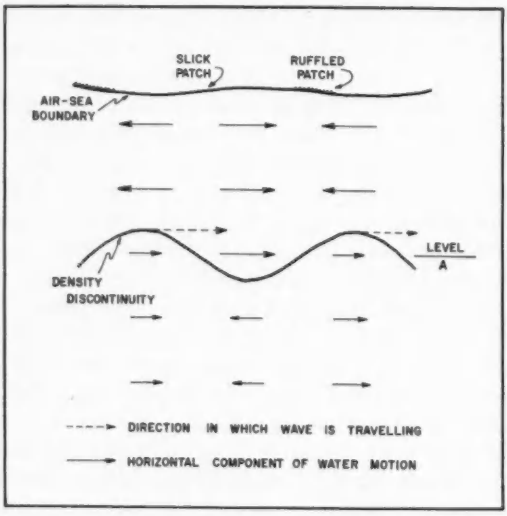

FIG. 25. Diagram illustrating direction of water motions in presence of internal wave at density discontinuity.

the minimum in the down-inlet flow may be an apparent flow due to progressive internal waves. It is also possible that internal waves in the deep water may be at least partly responsible for the apparent net flow out of the inlet which was discussed above and which appears to be associated with the deep current observations.

CONCLUSIONS

The current observations in Knight Inlet, together with previous ones in Knight, Toba and Bute Inlets, indicate that significant currents occur throughout the water column from surface to close to the bottom. The amplitude of the currents ranges up to 150 cm/sec at the surface, to 50 cm/sec at 70 m depth in water of 75–80 m depth, and to 25 cm/sec at 300 m depth in water of 350 m depth. These currents clearly possess both oscillatory and net components, the former being of tidal period. In addition, the measured currents contain very significant transverse as well as longitudinal components.

The conclusions with regard to the longitudinal components are summarized first. At a shallow (75–80 m) section of the inlet, the oscillatory component was in the same phase from surface to bottom. In the no wind condition, there was a two-layer flow, with a net outflow in the upper half and inflow below this. In the presence of an up-inlet wind, there was a three-layer net flow, up-inlet in the top 5–10 m, down-inlet in the mid-depths, and up-inlet in the bottom 15–20 m.

At a deeper (350 m) section the up- and down-inlet (flood and ebb) flows started at 50–100 m and spread to greater depths, so that there was generally

an appreciable phase difference between the oscillatory currents at different depths. There was also an oscillatory component in the surface layers with a superimposed net outflow and very marked wind effects. In light wind conditions there was a strong net outflow in the surface 5–10 m, but a strong up-inlet wind inhibited the surface outflow for 20–30 hours, with some indication that in this period the increase of slope down-inlet due to river run-off into the head of the inlet became sufficient to overcome the wind stress. With a down-inlet wind the net flow occurred in four layers — outward from the surface to 40 m and from 100–250 m, and inward between 40 and 100 m and below 250 m. With an up-inlet wind there were three net flow layers — out between 50 and 200 m, and in from surface to 50 m and below 200 m.

The transverse components in the deep section were at times as large as the longitudinal components but their average values were smaller. The directions and magnitudes appeared to vary randomly and did not show any significant tidal component. In the shallower section, there was some apparent tidal periodicity in the transverse components, but this is attributed to an effect of the bottom topography which apparently results in the flood and ebb directions being less than 180° apart in the inlet section studied.

Calculations of fresh water transport in the upper layer gave values which were in fair agreement with the previously calculated mean values for the time of year. However, calculations of the net transport across the whole inlet section gave values considerably in excess of the fresh water transport. This suggests that it may not be correct to assume, as was done for these calculations, that the velocity profile in mid-inlet is quantitatively typical of the entire cross-section. It is unlikely that this discrepancy is due to an instrument fault, and it must be pointed out that this excessive net transport is still only of the order of 10% of the total tidal transport through the section during one flood or ebb.

Observations of the ship motion at the anchor stations showed that it was considerable, and since it is argued that all or most of this motion appears in the current measurements in addition to the actual water motion, it was necessary to correct for it. For a large proportion of the time, the main component of ship motion was across inlet, and would therefore not have a major effect on the longitudinal component of current to which most attention was directed. However, lack of information on the ship motion would certainly make the measurements more difficult to analyse.

The analysis of this set of observations suggests several improvements in technique:

(1) It would be advisable to minimize ship motion by multiple anchoring if equipment were available, since the correction for its consequences is tedious as well as uncertain at the greater depths.

(2) An increase in the number of depths of observation would render the profiles, and deduced net flows, much more convincing. This increase could be achieved with the use of a direct (deck) reading current meter, rather than the slow Ekman meter.

(3) Water density profiles (i.e. salinity and temperature) should be measured frequently during the current measurement series. It would be helpful, for interpretation, to do this near the inlet head as well as at the current measurement location.

(4) Current profiles should be studied at several locations across a section.

(5) A recording tide gauge should be installed near the ship's position, and also toward the head of the inlet to give some indication of wind set-up.

(6) Measurements of wind speed at two or more heights would be valuable for the calculation of wind stress.

ACKNOWLEDGEMENTS

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Proximate Analysis of Pacific Herring (*Clupea pallasii*) and an Evaluation of Tester's "Fat Factor"[1]

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ABSTRACT

Samples of Pacific herring (*Clupea pallasii*) were obtained from commercial catches made at approximately monthly intervals for a period of a year. These samples were analysed for their water, oil, protein and ash content. The seasonal variations obtained in the analytical values in general confirmed those observed previously for this species of fish.

When Tester's "fat factor" determined by dividing the weight of the fish by its weight in water was used to calculate the oil content of herring, the average deviation of the calculated oil content from that determined experimentally was 15% and the range of deviation was 2 to 49%. Use of the "fat factor" as a practical means of determining the oil content of herring is not recommended.

INTRODUCTION

Proximate analyses of herring have revealed marked variations in the fat and water content of various tissues depending on the time of the year when the fish are caught. Milroy (1906; 1908) made the first careful study of this phenomenon and showed that the changes could be related to the feeding and spawning cycles of a given population of fish. These observations have been confirmed and extended by other workers (Johnstone, 1914; Lovern and Wood, 1937). Bruce (1924) further showed that at any given stage of sexual maturity the fat content of herring muscle was increased by age.

In addition to changes in the fat and water content of herring, seasonal changes in protein have also been recorded (Lovern and Wood, 1937).

It has been shown that the changes in proximate composition which the Pacific herring (*Clupea pallasii*) undergoes during its development are similar to those recorded for other species of herring caught elsewhere in the world (Hart *et al.*, 1940). In addition, a reasonably good correlation was obtained between the oil content of the fish and a "fat factor" obtained by dividing the weight of a fish in air by its weight in water (Tester, 1940).

The results recorded here were obtained in the course of an investigation of factors responsible for seasonal variations in the viscosity of condensed herring solubles. Samples of herring caught at approximately monthly intervals were obtained at local reduction plants over a period of a year and subjected among other tests to a proximate analysis. The results of the latter, in general, confirm those obtained previously on Pacific herring (Hart *et al.*, 1940).

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Since the correlation observed by Tester (1940) between the oil content of herring and his "fat factor" had been tested for seasonal fluctuation on herring caught over only a limited period during a year, the observations were extended to include determinations on all of the samples obtained in this present investigation.

METHODS

On approximately the fifteenth day of each month from January 15 to November 15, 1957, samples of fresh herring were taken at a local reduction plant from catches made by commercial herring boats in the waters off the southeast coast of Vancouver Island. Due to a strike in the herring fishery in the Vancouver area, the December 1957 and the January and February 1958 samples were obtained from a reduction plant in Prince Rupert and were representative of fish caught in waters approximately 500 miles north of those from which the other samples had been taken.

When sex determination was possible the fish were separated into males and females. Each group analysed at each monthly interval was composed of ten fish. After selection of the fish the physical measurements required for the determination of the condition factor were obtained as described by Tester (1940).

All the fish in a group were then pooled, ground in a meat grinder, and finally homogenized in a Waring Blendor. If analyses were not carried out immediately, the homogenate was frozen and maintained at –10°C until used.

Moisture was determined by drying weighed samples to a constant weight using a Cenco moisture balance[2]. Oil was determined by an approved method of analysis (Association of Official Agricultural Chemists, 1945). Ashing was carried out in a muffle furnace at 550°C. Total nitrogen was determined by the macro-Kjeldahl procedure and expressed as protein by multiplying the value obtained by 6.25.

The results reported are the average of analyses of the homogenates carried out in triplicate and are expressed as percent of the whole fish on a wet-weight basis.

RESULTS

Proximate Analyses

The results of the analyses are presented in Table I.

Oil levels in the herring samples reached their lowest values in March. Between March and April the fish spawn. The oil level in April was nearly double that in March and remained in this range during May. In June, the fat content of the fish reached its peak and then declined until spawning time the following year. There was a reciprocal relation between the water and the fat content of the fish. No significant differences between males and females were apparent.

No trends could be detected in the ash content of the fish with time of year.

Protein levels were lowest in the fish during the months of April to August when the gonads could not be detected. As the gonads developed there was a

[2]Central Scientific Company of Canada, Ltd., Toronto. Cat. No. 26,675.

gradual increase in the total nitrogen content of the fish, and this, expressed as protein, reached its peak in January and February. Whether the slight drop in March is significant cannot be stated.

These findings are, in general, similar to those recorded by Hart *et al.* (1940).

TABLE I. Proximate analyses of Pacific herring (*Clupea pallasii*) caught at monthly intervals for a year.

Month	Sex	Gonads[a]	Water	Fat	Ash	Protein
1957			%	%	%	%
January	Male	15.30	70.10	9.47	2.47	17.59
	Female	9.99	70.37	9.50	2.36	17.38
February	Male	16.41	72.09	7.76	2.35	17.84
	Female	16.20	72.00	8.04	2.28	17.00
March	Male	20.81	76.43	4.90	2.43	16.79
	Female	19.15	76.70	5.40	2.78	16.68
April	Undetermined	–	71.90	10.91	2.30	14.81
May	"	–	74.77	8.09	2.41	15.13
June	"	–	57.69	24.35	2.65	14.25
July	"	–	66.49	16.53	2.36	15.00
August	"	–	65.31	18.06	2.29	14.31
September	Male	3.68	64.20	17.61	2.34	15.44
	Female	2.40	63.40	18.01	2.37	15.31
October	Male	5.73	65.00	16.20	2.46	15.94
	Female	2.91	64.75	16.70	2.37	15.94
November	Male	10.60	66.80	14.40	2.41	16.90
	Female	4.02	68.30	13.05	2.45	16.61
December	Male	12.80	64.6	16.55	2.31	17.62
	Female	7.29	64.0	16.60	2.47	17.00
1958						
January	Male	18.15	69.1	11.66	2.28	17.69
	Female	14.69	68.6	11.72	2.39	17.75

[a]Expressed as percent of total body weight.

CORRELATION OF THE FAT FACTOR WITH OIL CONTENT

The *F* or "fat factor" was devised by Tester (1940) and determined by dividing the weight of a fish in air by its weight in water. He found it to be far superior to condition factors calculated on the basis of weight and length of the fish as an index of fatness (condition) of herring.

When the oil content of the herring and the corresponding *F* of the herring are plotted against the month of the year, a superficial correlation between the two values is apparent. A more rigorous analysis of the relation is presented in Table II.

TABLE II. Analysis of the relation between the "fat factor" and the oil content of herring.

Month	Sex	Fat factor (*F*)[a]	Oil[b]	Conversion factor[c]	Calculated oil[d]	Deviation[e]
1957			%		%	%
March	Male	8.98	4.90	.543	5.57	13.7
	Female	8.52	5.40	.633	5.28	2.2
April	Undetermined	15.9	10.9	.687	9.83	9.9
May	"	15.4	8.1	.527	9.53	17.8
June	"	44.0	24.4	.553	27.3	12.1
July	"	19.7	16.5	.838	12.2	26.1
August	"	27.3	18.1	.661	16.9	10.3
September	Male	26.0	17.6	.679	16.1	8.47
	Female	24.7	18.0	.728	15.3	15.0
October	Male	22.3	16.2	.725	13.8	14.7
	Female	22.6	16.7	.738	14.0	16.2
November	Male	22.0	14.4	.655	13.6	5.27
	Female	21.2	13.0	.615	14.1	8.36
December	Male	24.8	16.6	.667	15.4	7.14
	Female	25.4	16.6	.653	15.8	5.11
1958						
January	Male	23.3	11.7	.500	14.4	23.8
	Female	22.7	11.7	.516	14.1	20.0
February	Male	22.9	9.54	.415	14.2	49.0
	Female	18.9	8.44	.446	11.7	38.9
			Average	.620		15.5

[a]Weight of the fish in air divided by its weight in water.
[b]Determined experimentally.
[c]Obtained by dividing % oil (Column 4) by "fat factor" (Column 3).
[d]Obtained by multiplying "fat factor" (Column 3) by the average conversion factor for the year (bottom of Column 5).
[e]Deviation of the calculated oil content (Column 6) from the experimentally determined oil content (Column 4).

By dividing the oil content of each sample by its *F* a conversion factor is obtained enabling the oil content of an unknown sample of herring to be calculated from a knowledge of its *F*. The conversion factors calculated in this way are given in column 5 of Table II. It is quite evident that these conversion factors are not constant. The conversion factors obtained for each month were then averaged. This average was found to be 0.620 for the year. With this average conversion factor a value for the oil content of the herring at each monthly interval calculated

from the experimentally determined F was obtained. This theoretical oil content is presented in column 6. The percent deviation of this oil content from the actual oil content is given in column 7. The average deviation from the true value was 15.5% and the range in the deviation was 2 to 49%.

DISCUSSION

Since this investigation was completed the change in the viscosity of condensed herring solubles with season has been related to the gelatin content of the solubles (McBride *et al.*, 1959). It has been found that there is an increase in

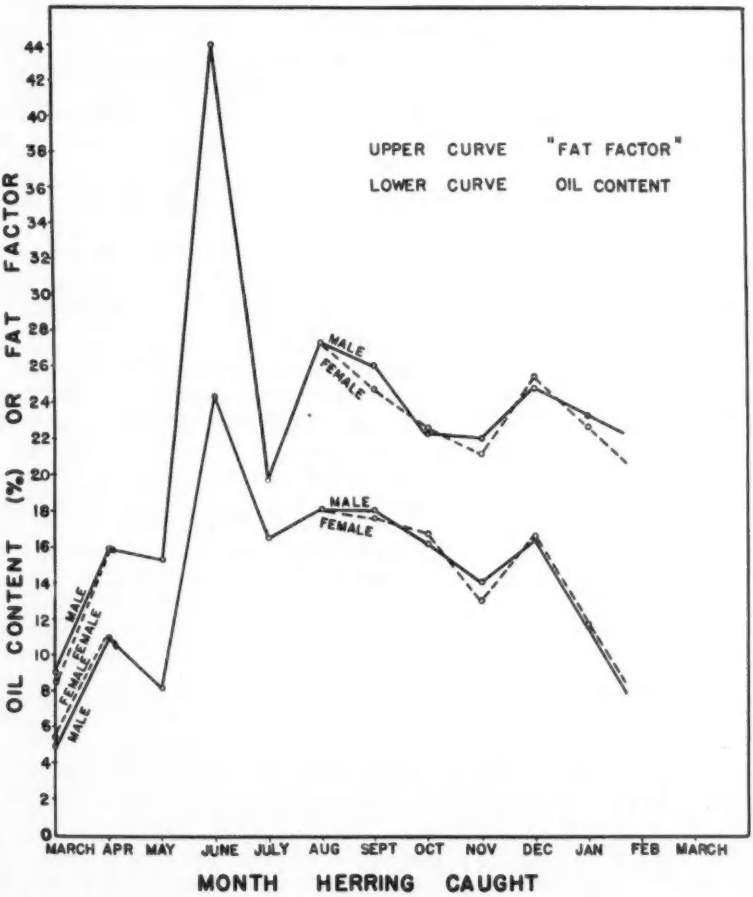

FIG. 1. Variations with season of the oil content and the "fat factor" of Pacific herring (*Clupea pallasii*). Where each curve breaks into two lines, sex could be differentiated. The dotted line represents values for females and the solid line for males.

the deposition of collagen in herring as the gonads develop and this may be at least partially responsible for the increase noted in Table I in the total nitrogen of the fish from summer to the following spring.

It is a well-known fact among reduction plant operators that more fish meal is obtained per ton of herring from winter fish than from summer fish. The variation is from about 310 lb of fish meal per ton of herring in the summer to about 370 lb per ton in the winter; an increase of approximately 20% in the yield of fish meal from winter-caught herring[3]. Examination of the data in Table I reveals that from April to August the average protein content of the herring was 14.7% while from December to February it was 17.5%. This represents a 19% increase in total nitrogen in the winter herring and could well be responsible for the increased yield of fish meal from these fish.

Examination of Fig. 1 reveals that the gradual drop in oil content of the herring after the August sample was taken was interrupted in December, when a higher oil content was recorded. This change correlates with the fact that the December, January and February samples were of fish caught in more northern waters where the herring is known to mature and spawn later in the season (Stevenson, 1949). This observation provides further evidence of the close relation between oil content and sexual maturity of the fish.

The results recorded here indicate that Tester's "fat factor" is not suitable for accurate estimates of the fatness of herring. Although the poorest correlations occurred with the most mature fish, a considerable lack of correlation was also observed on several occasions with less mature fish.

Although this lack of correlation was not due in these experiments to inability to obtain reproducible "fat factors" on any given sample of fish, the determination of the "fat factor" is a technique requiring the exercise of considerable care. Even greater variations than those recorded here might thus be expected under most field conditions. Determination of the "fat factor" as a practical means of determining the oil content of herring is therefore not recommended.

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[3]We are indebted to Mr. M. Kreuger of the Prince Rupert Fishermen's Co-operative Association for this information.

Condensed Fish Solubles. A Review of its Preparation and Properties[1]

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ABSTRACT

The chief methods of preparing condensed solubles are by concentrating stickwater after first treating it with acid or enzymes to remove or destroy interfering proteins. When acid treatment of the stickwater is used prior to its centrifugation and concentration, there is a change in the viscosity of solubles with season, which can be attributed to changes in its gelatin content. The effect of the gelatin can be overcome by the use of enzymes.

Stickwater can be preserved with acid, sodium acid pyrophosphate or penicillin prior to its conversion to solubles.

The amino acid and vitamin content of condensed solubles is discussed with particular reference to factors such as freshness of the fish, degree of spoilage of the stickwater and methods of processing the solubles which cause variations in the levels of these nutrients.

The composition of the solubles is also determined by the species of fish used, the age and extent of maturation of the fish, and by the type of material (whether whole fish or fish scraps) from which the solubles is prepared.

The use of condensed fish solubles as a feed supplement is discussed. The need for using fish solubles of known history both in practical rations and in nutrition studies is stressed.

INTRODUCTION

Information about the preparation and properties of condensed fish solubles is widely scattered. Because of the considerable current interest in the use of condensed solubles as a source of growth stimulating factors in rations for poultry, it is felt that a summary of information regarding the preparation and properties of this product would be of interest.

SOURCE

Condensed solubles is a product obtained by the treatment and concentration of fish stickwater. Fish stickwater is a by-product in the production of fishmeal by the wet-reduction process (Tressler and Lemon, 1951). In this process the fish are cooked and then pressed. The presscake is dried and becomes fishmeal. The press liquor which contains both oil and a water solution of some of the soluble components of the fish is separated into oil and water phases either in settling tanks or by centrifugation. The water phase or stickwater contains 5 to

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7% total solids, about 1% insoluble solids and 1 to 2% oil. About half of the solids (2.4 to 3.5% depending on the season and other factors) is nitrogenous material expressed as protein. Of the latter about 8% is true protein and the remainder is composed of smaller molecules (Beall, 1934). From 16 to 26% of the total protein of the original fish and a very large proportion of the water soluble vitamins can be recovered in the stickwater (Klungsøyr *et al.*, 1954).

RECOVERY OF THE STICKWATER

For many years stickwater was discharged into the sea as a waste product. In many cases it still is. When its value as a source of nutrients was realized, attempts at its recovery were made. One of the earliest of these was described by Johnston in 1938. He recommended that the stickwater be acidified to pH 4 and the coagulated protein removed by filtration. About half the total solids could be recovered in this way. No effort was made to concentrate or utilize the material dissolved in the filtrate.

Efforts to concentrate stickwater to a product with a high solids content were generally unsatisfactory since proteins present caused formation of a gluey viscous product. The effects of the protein were largely overcome by a procedure developed by Lassen (1945). In this procedure proteins were coagulated by acidification in a manner similar to that described by Johnston. The coagulated material was removed by centrifugation and added to the presscake for drying into fishmeal. After recovery of residual oil released by the acid treatment, the supernatant liquid was concentrated by multiple effect evaporation to a product called solubles. This product contains about 50% solids. Several descriptions of the process and of its advantages have been presented (cf. Ziemba, 1950). Many plants acidify stickwater merely as a preservative measure and concentrate the product without removing the coagulated protein. The presence of these solids in the final product in varying amounts contributes greatly to the varying physical properties of the resulting preparations.

Another method of producing a condensed product fluid at high concentration has also been devised (Gunther and Sair, 1948). In this method the proteins present in the original stickwater were converted to smaller fragments by the action of proteolytic enzymes. Condensation of the enzyme-treated stickwater to a product with a high solids content could then be effected without difficulty. Both the natural fish enzymes and commercially available proteolytic enzyme preparations can be used in this process.

The Norwegian Herring Oil and Herring Meal Industry's Research Institute developed a method of reincorporating the press liquor into the presscake after removal of the oil, to form what is referred to after drying as a whole meal. Usually, some concentration of the stickwater is effected before incorporation into the presscake (Anon., 1952a). The Norwegian organization also reports that stickwater can be condensed to a product containing 50% solids without preliminary acidulation or removal of insoluble solids if special precautions are taken to employ

vigorous stirring or forced circulation of the liquid during concentration (Sparre, 1953).

Other ways of producing condensed fish solubles appear to be largely minor variations of the two basic ways of treating stickwater, i.e., either with acid or with proteolytic enzymes prior to condensation to solubles. Alkali reduction processes have been studied (Anon., 1952b; Lovern and Preston, 1952) but have not been widely adopted because the nutritive value of the meal produced is low compared with that of other fishmeals (Carpenter and Duckworth, 1950). A method of evaporation of stickwater under pressure has been developed (Anon., 1958) and because of the higher temperatures involved gives rise to a more fluid product, presumably due to the breakdown of gelatin.

Efforts to convert condensed solubles to a dry product have met with little success. The product is excessively hygroscopic and many difficulties are encountered in its manufacture (Lee, 1956).

PROBLEMS IN THE PRODUCTION OF CONDENSED SOLUBLES

When the Lassen or acidulation procedure was used in the treatment of stickwater from herring caught off the Pacific coast of Canada, the physical properties of the solubles produced were found to vary depending on the season when the fish were caught (MacLeod *et al.*, 1955; McBride *et al.*, 1959a). While solubles prepared from herring caught in the summer was quite fluid, that produced from late fall and winter herring was viscous and tended to gel upon standing. Evidence was obtained which indicated that this increase in viscosity was due to a progressive increase in the gelatin content of the solubles produced from summer to winter (McBride *et al.*, 1959a). This change in gelatin content with season is shown in Table I. Solubles prepared from herring caught in August had satisfactory fluid

TABLE I. Changes in the gelatin content and the viscosity of solubles made from herring caught at approximately monthly intervals for a year (1957–58) (see McBride *et al.*, 1959a).

Month herring caught	Gelatin in solubles	Viscosity[a]	
		2 hr	24 hr
	%		
August	1.18	20.8	21.8
September	1.62	28.0	42.1
November	2.26	63.0	94.0
December	2.31	128.0	136.0
January	2.68	>150.0	>150.0
February	2.56	138.0	>150.0
March	2.42	>150.0	>150.0
April	0.99	23.0	23.6
May	0.99	20.3	20.7
June	0.91	23.3	24.2

[a]Stormer values — number of seconds for a paddle to turn 100 revolutions with a 200-g force applied. Determinations made at the indicated times after preparation.

characteristics and a gelatin content of just over 1%. The gelatin content increased to two and one-half times this level in January, February and March when these solubles were viscous and would solidify on standing in the cold. The sharp drop in gelatin content of the solubles which occurred in April corresponded to a period just after the herring had spawned. The level reached at that time was maintained during May and June.

The increase in gelatin content of the solubles paralleled the development of milt and roe in the fish and has been found to be due to an increase in the amount of collagen laid down by the fish in certain tissues, particularly in the skin, during maturation (McBride *et al.*, 1959b).

Since gelatin is not coagulated by heat or acid, it is not removed by the procedure developed by Lassen (1945) for the preparation of condensed solubles. Its effect, however, can be nullified by treatment of the stickwater with any one of a number of proteolytic enzymes (McBride *et al.*, 1959a). This is illustrated in Table II where the capacity of a proteolytic enzyme to produce a very fluid solubles with no capacity to gel is compared with the effect of acid treatment which can greatly reduce viscosity but does not prevent gelling.

TABLE II. Comparison of the effect of treating stickwater with acid and a proteolytic enzyme on the physical properties of the condensed solubles produced (see McBride *et al.*, 1959a).

Treatment prior to condensation	Properties of solubles		
	Stormer value[a]		Pour residue test[b]
	2 hr	24 hr	
	seconds		%
Untreated	199	352	100
Acidified to pH 5 and centrifuged	30	53	100
Enzyme digested[c]	17	18	3

[a]Number of seconds for a paddle to turn 100 revolutions with a 200-g force applied at the indicated times after preparation.

[b]Solubles were held at 50°F for 24 hours and then the container was upended. The amount retained in the beaker after 30 min was expressed as a percent of that originally present.

[c]Rhozyme B-6.

Since the capacity of gelatin to cause gel formation can be reduced by prior heat treatment of the gelatin solution (Ward, 1954), the application of heat to stickwater prior to its concentration to solubles was investigated. Heating for 2 hours at 212°F produced a considerable reduction in viscosity but insufficient to produce a wholly satisfactory product (McBride *et al.*, 1959a). Higher temperatures were not investigated because of the danger of destroying heat labile compounds of nutritional value.

If proteolytic enzymes are employed for the treatment of stickwater prior to its condensation to solubles, a further problem arises if the enzyme used has a pH optimum near neutrality. Bacterial spoilage of stickwater occurs very rapidly at or near a neutral pH even when the temperature is elevated (MacLeod *et al.*, 1955). The action of the bacteria not only produces an extremely offensive odour but also causes a considerable loss of solids from the stickwater in a very short period of time by transforming the dissolved material into volatile products. At 120°F, 40% of the total solids in stickwater was lost in 48 hours (Idler *et al.*, 1955). The use of sodium acid pyrophosphate to prevent the decomposition of fish press liquor has been recommended (McFee, 1951). A level of 0.25% was found to be required to prevent the decomposition of herring stickwater (Idler *et al.*, 1955). Effective at much lower concentrations are certain of the antibiotics, particularly penicillin. A level of 1 ppm of penicillin completely prevented solids loss for a period of 49 hours at 140°F (Idler *et al.*, 1955). The effect of the penicillin is not permanent, however, and a test under plant conditions revealed that decomposition was delayed for 48 hours after which time, probably due to the ascendency of a penicillin-resistant flora, rapid decomposition of the stickwater took place (Thomson *et al.*, 1956). The delay in spoilage resulting from the addition of penicillin is sufficient to provide a considerable margin for processing stickwater under most plant conditions and the low cost of even clinical grade penicillin is such that the value of the solids saved by the addition of the penicillin far exceeds the cost of the antibiotic added. Furthermore, prevention of bacterial spoilage in the stickwater will give rise to a solubles of higher nutritive value (Lassen *et al.*, 1949; Ney *et al.*, 1950).

To determine whether a sample of condensed solubles has the desired physical properties it is customary to determine viscosity by the application of the Stormer test (Fischer, 1950). In the Vancouver area a solubles is not considered suitable for commerce if the Stormer viscometer reading for a 200-gram load exceeds 30 seconds. If the product contains appreciable amounts of gelatin, the Stormer value obtained will vary considerably, due to thixotropic effects, depending upon the time elapsed since the preparation of the product. Furthermore, once the product has actually gelled, the Stormer test is unsatisfactory as a measure of gel strength. Results of studying methods for measuring the viscosity of solubles have revealed that a combination of tests is required to evaluate properly the physical properties of solubles (Thomson *et al.*, 1958).

Methods for unloading, storing and mixing fish solubles with animal feeds have been recommended together with the following standards for fish solubles upon arrival at the feed mill: 50% solids, 32% protein, not more than 0.8% ammonia nitrogen, not more than 6% fat and not more than 6.1% salt (Anon., 1956a).

NUTRITIONAL VALUE OF SOLUBLES

The chief value of condensed solubles lies in its use as a supplement in animal feeds. A typical analysis of condensed sardine solubles from the data of Lassen and Bacon (1946) is presented in Table III.

TABLE III. Typical analysis of condensed sardine solubles (from Lassen *et al.*, 1951).

Constituent	Amount present
Proximate analysis	*% by weight*
Total solids	50.0
Fat	2–6
Ash	8.86
Protein (N × 6.25)	33.5
Free amino acid nitrogen	0.54
Potassium	1.93
Sodium	1.87
Phosphorus	0.85
Calcium	0.087
Iron	0.025
Copper	0.007
Amino acid composition of total crude protein	*% by weight*
Arginine	4.34
Histidine	5.79
Lysine	4.87
Leucine	4.67
Isoleucine	2.73
Valine	2.98
Phenylalanine	2.33
Tryptophan	0.35
Methionine	1.51
Threonine	2.35
Glycine	6.73
Glutamic acid	8.44
Vitamins	*μg/g*
Thiamine	4.0
Riboflavin	20.0
Niacin	325
Calcium pantothenate	40.0
	Int. units/g
Vitamin A	4
	A.O.A.C. units/g
Vitamin D	2

Before the discovery of vitamin B_{12} and the recognition of its "animal protein factor" activity, condensed solubles was widely used in animal rations as a rich source of the "animal protein factor". Since 1948 this function of solubles has been largely replaced by the use of vitamin B_{12} concentrates or crystalline vitamin B_{12}. Data from Vyver (1952) show the high level of vitamin B_{12} in fishery products, particularly in herring and sardine solubles (Table IV).

The vitamin B_{12} content of herring stickwater and of the condensed solubles prepared from it has been reported (Tarr, 1955). The results indicated that the vitamin B_{12} content of condensed solubles (about 0.4 mg/lb on a dry weight basis)

is almost invariably somewhat lower (by about 25%) than that of the stickwater from which it is produced. In this study, samples of solubles were collected in fish reduction plants at intervals from the middle of November to the end of February. No variations in B_{12} content of the samples were evident over this period.

TABLE IV. Level of vitamin B_{12} in various feed supplements (from Vyver, 1952).

Substance analysed	Vitamin B_{12} content
	$\mu g/g$
Menhaden meal	62
Redfish meal	94
Redfish solubles (dry basis)	143
Sardine fishmeal	154
Sardine solubles (dry basis)	391
Herring fishmeal	259
Herring solubles	299
Cod and haddock meal	95
Meat scrap	36
Liver meal	310
Crude casein	104
Plant products	0–3

The essential amino acid content of condensed herring solubles has been reported (Ney *et al.*, 1950). The four samples of condensed fish solubles examined contained variable amounts of essential amino acids and the levels when compared with those in herring meal were considerably lower (Table V). Sample 2 of the condensed solubles was reported to possess a rather foul odour indicative of considerable bacterial putrefaction. Work by Lassen, Bacon and Dunn (1949) has shown that such putrefaction may result in a marked destruction of essential amino

TABLE V. Essential amino acids in condensed herring solubles and herring meal (data from Ney *et al.*, 1950).

Material analysed	Nitrogen	Arginine	Histidine	Isoleucine	Leucine	Lysine	Methionine	Phenylalanine	Threonine	Valine	Tryptophan	Tyrosine
	%	*grams of amino acid per 16 g of nitrogen*										
Condensed fish solubles												
Sample 1	4.4	4.5	1.0	4.5	6.2	4.1	2.6	3.0	2.2	3.9	–	1.4
2	6.2	1.4	0.5	1.8	2.4	3.2	0.7	1.1	1.2	1.9	1.2	0.29
3	4.3	3.2	1.8	2.2	3.4	5.0	1.5	1.7	2.1	2.0	2.4	0.35
4	5.1	4.7	–	2.5	4.4	5.7	1.8	2.0	2.4	2.7	2.0	0.40
Herring meal												
Sample 1	11.3	8.0	2.3	6.6	8.1	8.3	2.9	4.5	5.1	5.8	0.96	1.4
2	12.7	7.9	2.4	6.7	9.4	8.0	2.8	4.4	5.1	5.9	0.88	1.4
3	13.2	8.3	2.6	6.8	9.3	7.9	2.7	4.3	5.5	5.9	1.2	1.6

acids and this may well have accounted for the irregular results obtained with the sample. The California workers found a general decrease in the total content of the individual amino acids with increasing spoilage of the stickwater from which the solubles was prepared. In one case a 38% decrease in cystine and a 99% decrease in valine was observed. When chicks were fed a diet containing 10% fish solubles as the main protein source it was found that the growth-promoting action was reduced by spoilage of the raw material but that the appearance of the birds and the palatability of the meat was not affected (Lassen *et al.*, 1949).

There was no significant difference in the nutritional value of herring solubles prepared by the two principal methods, acid and enzyme treatment of stickwater, when samples of each type of solubles were used as a supplement in rations for growing chicks (March *et al.*, 1958).

The age and quality of the fish from which the stickwater is prepared is another factor influencing the chemical composition of the solubles. Stickwaters prepared from fresh herring and from herring processed after 31 days were found to contain respectively 16% and 26.4% of the total protein in the fish. Stickwater from stored herring contained 74% of the pantothenic acid, 63% of the niacin, 56% of the riboflavin and 52% of the vitamin B_{12} in the original fish (Klungsøyr *et al.*, 1954).

The method of manufacture of the meal and solubles can be a further factor determining the composition of the products. Evidence was obtained indicating that the manner of pressing the stickwater from the presscake may influence the distribution of riboflavin, nicotinic acid and vitamin B_{12} between the solubles and the meal (Karrick and Stansby, 1954).

The availability of synthetic vitamins or their concentrates has limited the use of condensed solubles as a source of known vitamins in animal rations. As the amino acid analyses show, there are also better sources of protein than this by-product. Evidence has been obtained, however, indicating that condensed solubles contains one or more unidentified factors capable of stimulating the growth of poultry. Chicks have been used most frequently in these studies (Lassen and Bacon, 1946; Biely *et al.*, 1954; Camp *et al.*, 1954; Murthy *et al.*, 1957; Arscott, 1956) but ducks (Scott and Parsons, 1957) and turkey poults (Donovan *et al.*, 1958; March *et al.*, 1959) have also been reported to respond to the inclusion of condensed solubles in the diet. As a result of these findings there is a renewed interest in and an increasing tendency toward the inclusion of condensed fish solubles as a supplement in poultry rations.

CONCLUSION

There is a tendency among feed mill operators and research workers to consider condensed fish solubles as a uniform and readily reproducible product. The composition of fish solubles, however, will vary considerably depending upon a number of factors. For instance, differences in composition of fish solubles can be expected depending on the species of fish used to prepare the solubles. Although herring, sardine and menhaden are the principal fish used in the preparation of meal and solubles, other species are used in some cases. Furthermore, solubles

may be the by-product made by reduction of fish scraps arising from filleting or canning operations and hence would not represent extractives from the whole fish. One solubles available commercially comes from a tuna packing operation in Southern California and is fortified with visceral material (Anon., 1956b).

Within a species of fish, marked variations in body composition have been noted depending upon the extent of maturation of the fish (McBride *et al.*, 1959a; Channon and El Saby, 1932; Idler and Bitners, 1958). Changes in the sexual state of the adult fish are cyclic in nature and are reflected in seasonal variations in the composition of the solubles produced from the fish (e.g., Table I).

Finally, as data quoted in this review have clearly shown, the composition of condensed solubles will also depend upon factors associated with the management of the reduction plant. Variations in composition of the solubles will occur depending upon the freshness of the fish used for reduction, the type of machinery employed in the reduction operation, and the extent of bacterial decomposition of the stickwater produced.

Although studies on the growth-promoting factors in fish solubles have now been pursued with undiminished vigour for a period of ten years, there is very little agreement between laboratories as to the nature of the growth-stimulating substances present or to the extent of the responses obtained. Although the variation in results may be ascribed in part to differences in the types of basal rations and to the history of the livestock used, what may well be an even more important source of variation is the composition of the fish solubles tested. In research reports on the use of condensed fish solubles in poultry and livestock rations, the source or history of the sample tested is almost never included, and no indication is given that such factors have been considered in the interpretation of the results obtained. Truly definitive conclusions regarding the growth factor potential of condensed fish solubles will have to await studies with carefully standardized preparations obtained from fish of known species, age, and stage of maturation. It is also evident that it would be desirable to establish standards for the preparation and composition of condensed fish solubles to provide feed manufacturers with supplements of predictable potency.

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Homing of Rainbow Trout to Inlet and Outlet Spawning Streams at Loon Lake, British Columbia[1]

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ABSTRACT

A four year field study was conducted on rainbow trout (*Salmo gairdneri*) spawning in the inlet and outlet of Loon Lake. Young and adult trout were trapped and marked in both streams. About 5000 fish spawn in the outlet between mid-March and June; about 22,000 spawn in the inlet between late April and July. Outlet young either enter the lake by late summer or overwinter in the stream and enter the lake next spring or summer. Most inlet young enter the lake in their first year. Return as adults, of fish which had been clipped while entering the lake as young, indicated that about 94% of fish originating from each end homed to their parent stream. Because of the large number of inlet spawners, about a quarter of the outlet spawners are strays which had hatched in the inlet. Recovery of marked fish, movement of adults within the lake, and experimental transfer of adults and young between streams, all indicate that inlet and outlet spawners do not differ genetically in their responses to current. The biological and applied significance of homing, and its possible mechanisms, are discussed.

INTRODUCTION

Rainbow trout, like several other species of freshwater fishes, are capable of spawning either in inlet streams entering lakes or in outlet streams leaving them. The *upstream* struggle of salmonid fishes during their spawning migration is familiar, but paradoxically, similar fish will on occasion move *downstream* before spawning. The two types of spawning may occur in the inlet and outlet of a single lake.

The subsequent behaviour of young resulting from such spawnings presents a further enigma, for if fry hatched in the two types of stream are to regain the lake from which their parents came, they must at some stage in their development move in opposite directions with respect to stream current.

Two kinds of explanation might be offered for the opposite current reactions of trout in inlet and outlet streams. On the one hand, there may be two genetically distinct types of trout, hereditary "inlet spawners" and hereditary "outlet spawners", with different innate responses to current. On the other hand, environmental differences between inlet and outlet streams may be responsible for producing opposite current responses in genetically similar fish.

The occurrence within one lake of two genetically distinct types of spawners of the same species would have considerable biological significance, as it would offer a possible mechanism for sympatric speciation. The applied significance would also be great, for if each type of fish were adapted to one type of spawning stream it would behoove fishery managers to plant each lake with the type suited to the spawning facilities available.

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The appropriate behaviour of both young and adult trout in inlets and outlets may, however, be dictated solely by the environment. If so, selection has presumably produced a set of responses innate in all trout, matched to certain environmental differences existing between most inlets and outlets, in order to produce the appropriate responses. In this case, knowledge of the factors involved would again be of applied as well as biological significance, because of the bearing on such problems as guiding fish at dams or diversions.

A study of inlet and outlet spawning of rainbow trout, *Salmo gairdneri* Richardson, was started by the British Columbia Game Commission (now the Fish and Game Branch of the Department of Recreation and Conservation), at Loon Lake in 1953. A program including trapping and marking of both young and adult trout was pursued for four years, followed by laboratory studies at the University of British Columbia on current responses of young trout. This paper reports on those results of the study which indicate whether or not trout in Loon Lake tend to "home" to inlet or outlet streams, and, if so, whether there is sufficient straying to preclude the possibility of two genetically distinct types in the lake.

GEOGRAPHY OF THE AREA

Loon Lake is situated in a narrow valley at an elevation of 2820 feet about 12 miles east of Clinton on the southern interior plateau of British Columbia. The lake is approximately 8 miles in length and varies between ¼ and ½ mile in width. The shores drop off steeply to a depth exceeding 100 feet along most of the length of the lake; maximum depth is 213 feet.

The principal inlet stream enters the northeast end of the lake, draining Upper Loon Lake, about 6 miles to the northeast, and other small lakes and marshes to the southeast (Fig. 1). Other very small inlet streams enter the lake, but most of these do not flow permanently. The outlet, draining the southwest end of Loon Lake, maintains a fairly level gradient to a point about 1300 yards below the lake, where it is joined by Hihium Creek which drains Hihium Lake some 8 miles to the east. Below this junction the outlet gradient increases until it drops over a series of rapids and waterfalls impassable to fish, about 4 miles from the lake.

Rainbow trout, native to Loon Lake and the only species of fish present, spawn in both its inlet and outlet streams. In the inlet stream the spawning area begins about ½ mile above the lake (Fig. 1), near the site of Inlet Trap 1, and extends for over a mile upstream beyond this point. In the outlet stream the majority of spawning takes place in the first 1000 yards below the lake, although some fish spawn in Hihium Creek above its confluence with the outlet, and in the outlet below this junction. Movement of fish between Loon Lake and either Hihium or Upper Loon Lake is probably rare and of negligible importance in this study.

OUTLINE OF STUDY

Several two-way fish traps were constructed in the outlet and inlet streams and their tributaries, to study runs of spawning trout leaving the lake, and to record movements of adults and young within the various streams. The locations of these traps are shown in Fig. 1.

Inlet Trap 1 was situated about half a mile from the northeast end of Loon Lake on the first substantial gravel footing above the stream mouth. The inlet between this trap site and the lake meanders through willow swamp and hay meadows and probably provides very little spawning gravel. Inlet Trap 2, approximately

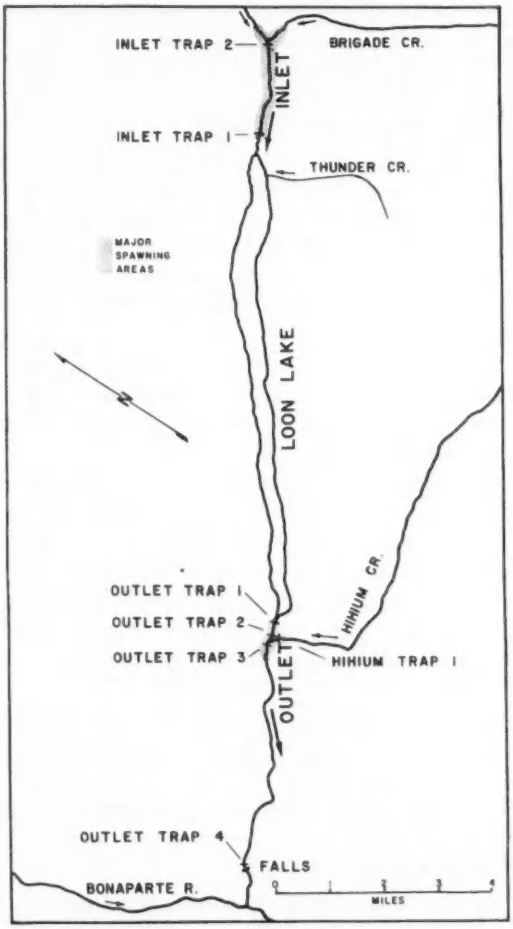

FIG. 1. Location of spawning streams and trap sites in Loon Lake system.

2½ miles from the lake, was located above most of the inlet spawning areas, although a few hundred adults spawned above this trap.

Spawners moving down the outlet stream encountered Outlet Trap 1 about 200 yards below the lake. Limited patches of gravel were present in the short distance between the lake and Outlet Trap 1, but probably relatively few adults

spawned in this section of the stream. Most adults spawning in the outlet utilized the section between Outlet Trap 1 and Outlet Trap 2 — 1050 yards below the lake and 250 yards upstream from confluence of Hihium Creek. Traps were also maintained for varying periods on Hihium Creek 70 yards above its confluence with the main outlet (Hihium Trap 1), and on the main outlet 50 yards below this confluence (Outlet Trap 3). These latter two traps demonstrated that a few adults came down the outlet as far as the confluence; some turned up Hihium Creek before spawning and some passed on downstream below Outlet Trap 3. Outlet Trap 4 was installed at the impassable falls 4 miles below the lake; very few fish, either adults or young, were taken this far downstream during the study.

Traps were operated for four years, from 1953 to 1956, during which time over 40,000 spawners were examined. Flooding during high water prevented continuous operation of all traps in all years. This difficulty was greatest in the inlet, where intermittent floods permitted examination of only about half the adult spawners in any one year. Estimates of the total inlet run were made by marking and recovery programs, except in 1956 when Inlet Trap 1 was installed for only a very short time.

Traps were maintained more easily in the outlet, although probably some spawners, particularly small males, bypassed Outlet Trap 1. An unknown number of adults, probably between 500 and 1,000 per year, were removed by Indians upstream from Outlet Trap 1.

Most traps were designed to catch and hold fish of all sizes moving in either direction. Each consisted of a diagonal screen fence with leads and holding boxes at either end, modified from the design of Shetter (1938). Hihium Trap 1 and Outlet Trap 4 were modified Wolf type traps (Wolf, 1951).

Each trap was usually attended at least once each day throughout the spawning season. Records were taken of the size, sex and condition of each fish caught, which was then marked and passed through in the direction it had been moving when captured.

In 1953 many of the adult trout caught in traps were marked with aluminum strap tags such as are clipped to wings of chicks. These numbered tags were clipped through the flesh on the upper side at the base of the tail. In 1954 and 1955 some fish were tagged with small Petersen disc tags behind the dorsal fin. Tagged fish were recovered in traps on the same or subsequent years, and during periodic checks of angler's catches taken in the lake.

All young trout caught moving up through Outlet Trap 1 in 1953 and 1954 were marked by fin clipping. A total of 23,187 outlet young were marked in this way. In the same years 4,777 fish, constituting only a small proportion of the young moving down through Inlet Trap 1, were also fin clipped. Details of the types of marks used are given later.

In addition to those reported here, other aspects were studied such as movement of adults within the spawning streams, and factors influencing current responses of the young. Only those data which bear directly on the question of homing are discussed in this paper.

OUTLINE OF LIFE HISTORY

In Loon Lake outlet, trout fry emerge from the gravel between late May or early June and early August. These fry remain in the outlet at least one month before some begin upstream movement into the lake. Between July and September several thousand fry enter the lake from the outlet. However, considerable numbers remain in the stream over the winter, and enter the lake as "fingerlings" the following spring. Thus, each spring and summer there are several thousand fry and several thousand fingerlings entering the lake from the outlet.

At the inlet, fry emerge between late June and late September, and move downstream shortly after emergence. Almost all enter the lake during their first

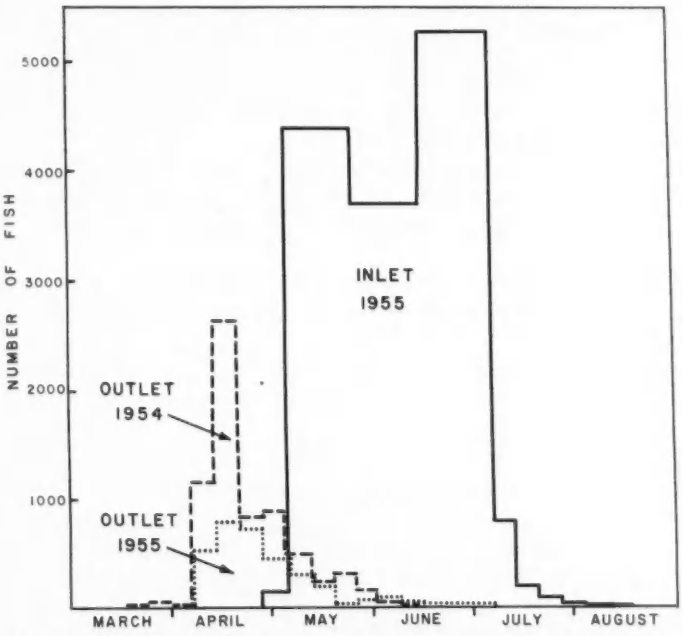

FIG. 2. Timing of rainbow trout spawning runs to outlet (1954, 1955) and inlet (1955) at Loon Lake. Numbers of fish in principal part of inlet run were estimated by tagging.

summer or autumn. Inlet fry output far exceeds that of the outlet and approaches 100,000 young fish annually. Only a few fry successfully winter over in the inlet and move into the lake the following year.

Spawning runs are composed largely of 4- and 5-year old fish, together with a few small individuals, mostly males, of age 3. Approximate size and timing of spawning runs in the outlet and inlet streams of Loon Lake are shown in Fig. 2. The majority of the outlet spawning run was enumerated in each year of the study, but due to flooding of traps on the inlet no complete count of inlet spawners was

possible. In each year, however, over 10,000 inlet spawners were examined. In 1955, by marking, and by examination of 11,869 fish from the inlet spawning run, the magnitude of the run was estimated during periods when complete counts were not made. The general patterns of inlet runs in 1953 and 1954 were similar to that given for 1955 in Fig. 2.

Mature fish begin moving into the outlet in mid-March before break-up of the lake ice cover. The run reaches a peak in middle to late April and may extend into July (when only a very few fish are taken). Most fish spawn in the upper portion of the outlet above Outlet Trap 2, but a few drop downstream to the confluence of Hihium Creek. Some of these evidently continue downstream below this point, but towards the end of the outlet spawning run a few fish turn upstream and spawn in the lower reaches of Hihium Creek. (The young hatching from these eggs move downstream from Hihium into the outlet stream, and at least some are known from marking experiments to subsequently ascend the outlet and reach Loon Lake.) Some fish, largely males, may reach sexual maturity in the outlet without entering the lake. These constitute an unknown but probably not large proportion of the outlet spawning population.

Spawning fish are first seen in appreciable numbers at the inlet in May, after the ice has left the lake. Large numbers of spawners enter the inlet during late June and early July; the run gradually falls off during the end of July and early August.

Thus, although there is some overlap in timing of outlet and inlet spawning runs, the majority of outlet spawners have left Loon Lake before the run to the inlet is well under way.

Spawning mortality is high, but some individuals do return to the lake from both streams and may appear in subsequent spawning runs.

HOMING, AS ADULT FIRST SPAWNERS, OF FISH MARKED AS YOUNG

The numbers of young trout marked by fin-clipping as they entered Loon Lake are shown in Table I. In 1953 and 1954 all fry (fish of age 0, in their first year of life) and fingerlings (immature fish in their second or, occasionally, third year of life) taken while moving upstream through Outlet Trap 1 were clipped. In the

TABLE I. Numbers of fry and fingerling trout marked while moving toward the lake in outlet and inlet streams in 1953 and 1954.
LV — Left ventral removed; RV — Right ventral removed; A — Adipose removed.

Year	Locality	Stage	Clip	Number
1953	Outlet	Fry	LV	6778
		Fingerlings	LV	9308
	Inlet	Fry	RV	2448
		Fingerlings	RV	358
1954	Outlet	Fry	LV	3727
		Fingerlings	LV + A	3374
	Inlet	Fry	RV	1778
		Fingerlings	RV + A	193

same years all fingerlings moving downstream through Inlet Trap 1 were clipped, but only a small proportion (less than 5%) of the fry were large enough to be clipped. Clipped inlet fry were therefore not typical of the inlet-hatched population in that they represented only the largest individuals (early-hatched, or fast-growing, or late migrants).

Recoveries of these clipped fish as adults spawning for the first time in 1954, 1955 and 1956 are shown in Table II. (Fish known from previous marking to be

TABLE II. Numbers of clipped adult first spawners among spawning runs to outlet and inlet streams, 1954–1956. Bold face figures represent homing fish.
LV — Left ventral removed; RV — Right ventral removed; A — Adipose removed.

Locality of recovery	Year	Number of adults examined (estimated total in parenthesis)	Clip recovery	Origin of clip recoveries	Number of clip recoveries	Estimated total clips
Outlet	1954	7,110	LV	1953 outlet fingerling	**174**	**174**
			RV	1953 inlet fingerling	0	0
	1955	3,997	LV	1953 outlet fry or fing.	**91**	**91**
			LV + A	1954 outlet fingerling	**50**	**50**
			RV	1953 inlet fry or fing.	8	8
			RV + A	1954 inlet fingerling	0	0
	1956	4,746	LV	1953 outlet fry or fing. or 1954 outlet fry	**527**[a]	**527**[a]
			LV + A	1954 outlet fingerling	**30**	**30**
			RV	1953 inlet fry or fing. or 1954 inlet fry	2	2
			RV + A	1954 inlet fingerling	0	0
Inlet	1954	12,417 (23,248)	LV	1953 outlet fingerling	1	2
			RV	1953 inlet fingerling	**3**	**6**
	1955	10,488 (19,870)	LV	1953 outlet fry or fing.	8	16
			LV + A	1954 outlet fingerling	1	2
			RV	1953 inlet fry or fing.	**25**	**49**
			RV + A	1954 inlet fingerling	**1**	**2**
	1956	141	LV	1953 outlet fry or fing. or 1954 outlet fry	0	...
			LV + A	1954 outlet fingerling	0	...
			RV	1953 inlet fry or fing. or 1954 inlet fry	**1**	...
			RV + A	1954 inlet fingerling	0	...

[a]This total is estimated to contain eleven 1954 outlet fry, on the basis of fish size and of known survival of marked segments of other year classes.

spawning a second or third time, which make up only a small proportion of the runs, are omitted from Table II and are dealt with on page 708.)

A strong tendency for fish to home to their parent stream is evident from examination of Table II. Of the clipped fish recovered each year and in each stream, many more were "homers" than were "strays."

In the following discussion various methods are examined of presenting quantitatively the degree of homing. These proceed from straightforward calculations which are based only on actual numbers of clip recoveries but which are biased by inequalities of marking and sampling intensities, to more elaborate methods which attempt a truer picture of overall homing and straying but which depend on estimates abstracted from the original data.

FIRST METHOD. According to the simplest calculation, in all three years 922 clipped fish were recovered as first spawners; of these 902 had returned to the stream in which they were originally clipped as young, and only 20 had strayed. Using these figures, homing at first spawning could be said to be 97.8%.

SECOND METHOD. However, because the degree of homing may be different in fish originating from the two ends, and because very different numbers of young were marked in the two streams, it is better to consider separately those marked recoveries which came from each rearing area. According to this method, of 882 recoveries actually sampled which originated from the outlet, 872 or 98.8% homed, while of 40 recoveries which originated from the inlet, 30 or 75.0% homed.

THIRD METHOD. Both the foregoing calculations are seriously biased by disproportionate sampling of the adult runs. The majority of the outlet spawners were examined for marks, while it was possible to examine only about half the inlet runs in 1954 and in 1955, and only a very small portion in 1956. This tends to lower the apparent homing of inlet-reared fish, as all inlet "strays" were counted in the outlet, while only a fraction of the inlet "homers" were discovered in the incompletely sampled inlet run. To avoid this difficulty, an attempt was made to estimate the *total* runs to both streams and to weight the number of recoveries in accordance with these totals.

Almost all adults moving downstream in the outlet were actually examined, either in Outlet Trap 1 or in Outlet Trap 2. A number of small adults, chiefly precocious males, apparently passed through the fence of Outlet Trap 1 without being captured, and were first recovered in Outlet Trap 2 which had a fence of finer mesh than had Trap 1. These fish were included in the total examined each year at the outlet. Also, an unknown number of fish, probably between 500 and 1,000, taken by Indians above Outlet Trap 1 are not considered.

At the inlet, many adults moved past Inlet Trap 1 during extensive periods of washouts or flooding. The total number of adults spawning in the inlet in 1954 was estimated by the marking (with tags or fin clipping) of 1,685 fish ascending the stream. Of these, 840 were recovered amongst 11,338 live and dead fish subsequently examined descending. The best estimate of the 1954 run, considering the sexes separately, was 23,248 fish.

A similar estimate was made of the number of adults spawning in the inlet in 1955. This was based on marking of 3,330 fish, and subsequent recovery of

1,450 of these amongst 8,573 fish sampled. Using a breakdown of the run into separate sexes, the best estimate of the 1955 inlet run was 19,870.

From the estimated total numbers of fish in the 1954 and 1955 spawning runs, the probable total numbers of clipped fish present can be calculated. The right-hand column of Table II shows these estimates which are based on the proportion of clips present in segments of the run actually sampled, considering the sexes separately. No estimate of clips present in 1956 was attempted because of the very small number of inlet spawners sampled.

A calculation of homing can be made, using these estimated total numbers of spawning clipped fish, which is not biased by the incomplete sampling of the inlet run. Only the 1954 and 1955 runs to both outlet and inlet can be compared, because no reliable estimate is available of the total number of clipped fish in the inlet run of 1956.

Of marked fish originating in the outlet, 315 were recovered as spawners in the outlet in 1954 and 1955, while an estimated 20 strayed to the inlet. This represents a homing of 94.0%. Of fish marked as fry in the inlet, an estimated 57 returned there to spawn, while 8 strayed to the outlet, representing a homing of 87.6%.

FOURTH METHOD. The foregoing satisfactorily describes the relative degree of homing, in 1954 and 1955, of fish clipped in 1953 and 1954, but does not

TABLE III. Calculation of homing as first spawners, in 1954 and 1955, of young entering the lake in 1953.

Source of young	Total young marked	No. spawning in 1954 & 1955		Total first spawners
		Inlet	Outlet	
Estimated returns, without adjustment for marking only a fraction of inlet young entering the lake				
Outlet	16,086	18	265	283
Inlet	2,806	55	8	63
Estimated returns, had all inlet young been marked				
Outlet	16,086	18	265	283
Inlet	81,643	1,600	233	1,833

describe the *total* number of homing and straying adults resulting from one year-class. The following calculations attempt to determine more completely the site of first spawning of those young which entered the lake, from either inlet or outlet, in 1953. The first two lines of Table III show actual numbers of clipped adults probably present in the 1954 and 1955 runs. (Data in this and following calculations are obtained from Tables I and II.) In the inlet only 2,806 of the 81,643 inlet-reared young entering the lake in 1953 were clipped. The next two lines are calculated on the assumption that had *all* the inlet young in 1953 been marked they would have yielded the same proportionate returns as those actually marked.

Homing of fish originating from either end can be calculated directly from data in Table III (which yields results similar to the previous calculations) but this procedure is still open to objection. Such calculations, although based on

reliable estimates (i.e. estimates made by sampling about half the inlet runs and the majority of the outlet runs) are still incomplete in that they represent only the return, (of young which entered the lake in 1953) as first spawners 1 or 2 years later. A considerable number of these fish did not spawn first until 3 years later, i.e. in 1956. The total outlet spawning run was checked in 1956, but only a very small sample (141 fish) was examined in the inlet.

Various methods were attempted of estimating the number of clipped fish in the 1956 inlet run, but none was satisfactory because of the many sources of error. Consequently the final calculation of homing in Loon Lake has been based on returns to the inlet in only 1954 and 1955, but to the outlet in 1954, 1955 and 1956. The proportion of homers and strays in the inlet in 1956 is, therefore, assumed to be the same as in the two previous years. This calculation differs from the foregoing in that fish spawning in one stream rather than fish originating from one stream, are considered together.

In this summation, only fry and fingerlings which entered the lake in 1953 are considered. Only adults spawning for the first time are included. All fish are assumed to spawn within 3 years after entering the lake as young. (In fact, a small number of females entering the lake as fry in 1953 may have spawned first in 1957; these must be ignored as no samples of spawners were taken in that year.)

Fish spawning in the *inlet* in 1954 and 1955 are considered first. The probable returns to the inlet in these years, had all young of 1953 been clipped, are available from Table III. A total of 1,600 inlet-marked homers and 18 outlet-marked strays would have spawned in the inlet in 1954 and 1955, a composition containing 98.9% homers.

A similar calculation may be made of the effect on composition of the *outlet* run of clipping all young at both ends in 1953. In this case all 3 years of recovery data are used. A total of 10 inlet-clipped fish were recovered as strays in the outlet (Table II); the assumption is made that this number would have been 291 had *all* 1953 inlet young been clipped. In the same three years 781 outlet-hatched homers were taken which originated from the 1953 clipping (Table II). Therefore, had all young been marked at both ends in 1953, a total of 1,072 clipped fish would have spawned in the outlet in 1954, 1955 and 1956, 72.8% of which would have been homers.

Having calculated the proportion of marked homers and strays spawning in each stream which result from marking all young entering the lake in one year, it is now possible to draw up a table showing the probable origin and composition of the whole inlet and outlet spawning population in any one year. A discrepancy in these calculations, which probably does not seriously alter conclusions regarding homing, is discussed on pages 705–708.

The size of the spawning populations has been taken as the average of all years for which estimates are available (21,559 in the inlet, 5,284 in the outlet). The proportion of second and third spawners is known in the outlet from marking and recoveries over several years, and is assumed to be the same in the inlet. All these repeat spawners are assumed to be returning to the stream of first spawning, as discussed in a later section. The probable number of repeat spawners has been

subtracted from the total for each run, and for each run the remainder has been split into homers and strays according to the percentages just calculated.

The average composition of inlet and outlet spawning runs so obtained is given in Table IV and presented graphically in Fig. 3. This is the best available

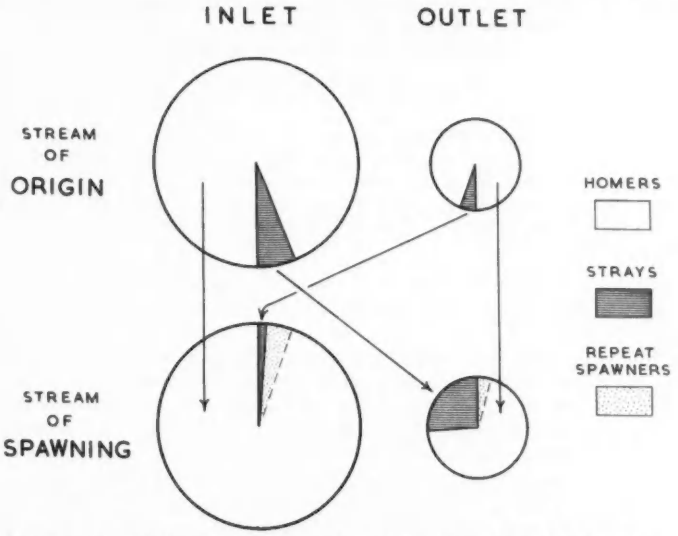

FIG. 3. Graphical representation of the composition of Loon Lake spawners, arranged by stream of origin (*above*) and stream of spawning (*below*). Areas are proportional to numbers of fish as given in Table IV.

representation of homing of the whole population. Considering the overall picture, homing at time of first spawning in Loon Lake may be said to be 93.8% effective. Moreover, on the basis of total run composition, there does not appear to be much difference in homing between inlet and outlet young. However, because of the greater contribution of young to the lake from the inlet, even the relatively small percentage of straying among these inlet-reared fish results in a quarter of the outlet run being composed of trout originating from the inlet.

TABLE IV. Best calculated average composition of spawning runs.

Origin	Spawning in Inlet	Spawning in Outlet	Precentage homing amongst first spawners
Inlet young	20,409	1,373	93.7 %
Outlet young	230	3,686	94.1 %
Repeat spawners	920	225	
(Total homing of first spawners = 93.8%.)			

DISCUSSION OF DISCREPANCY IN THE HOMING CALCULATION

The discrepancy mentioned previously, which appears in calculations of the average composition of spawning runs, will now be considered. It might be expected that the total

contribution to the outlet run, over several years, of one year's input of young to the lake, should equal the average size of the outlet spawning run in any one year. In the last calculation, marking all young entering the lake in 1953 from either end, is estimated to produce only 1,072 clipped first spawners at the outlet in 1955 and 1956. Yet the average outlet run is 5,284 fish, of which approximately 5,059 are first spawners. In other words after intensive marking of young at the start of the program, subsequent spawning runs contained an unexpectedly high proportion of unmarked fish. Several possible explanations for this discrepancy are listed below, and the likehood of each biasing the conclusions regarding homing is discussed.

1. SOME FISH ENTERING THE LAKE AS FRY MAY NOT RETURN TO SPAWN UNTIL FOUR YEARS LATER.

Thus the apparent total contribution of the 1953-marked young might have been greater had the 1957 spawning runs been examined. Independent evidence (derived from the proportion of clipped fish remaining in the anglers' samples in the autumn of 1956), suggests that a few 1953-clipped females would have returned first in 1957, but that this contributed only slightly to the discrepancy. Little distortion of the conclusions regarding homing would be expected from this source.

2. SPAWNING MAY HAVE OCCURRED IN AREAS NOT SAMPLED BY THE TRAPS, RESULTING IN FAILURE TO RECOVER ALL ADULT CLIP-RECOVERIES AND FAILURE TO COUNT AND MARK ALL YOUNG ENTERING THE LAKE.

Some spawning undoubtedly occurred in the short sections of gravel upstream from Outlet Trap 1 and downstream from Inlet Trap 1. These areas were small in contrast to the spawning areas enclosed by the traps, but they may have supported disproportionately heavy concentrations of spawners toward the ends of the spawning period (when fish have been found to move shorter distances away from the lake before depositing their eggs).

Some spawning is also known to occur in Thunder Creek, a very small stream entering Loon Lake near the main inlet (Fig. 1). No trout, adults or young, were seen in Thunder Creek on May 9, 1953 when the outlet spawning run was past its peak and the inlet run was beginning. However, on September 28, 1953, a few fry were evident for at least 200 yards upstream from its mouth (above which a sharply rising gradient and large-boulder bottom precludes the possibility of much successful spawning). The number of spawners using Thunder Creek is probably at most a few hundred fish, varying in different years depending upon water levels and the degree of blockage offered by a beaver dam at the mouth.

Lastly, some spawning might occur in spring-fed gravel along the lake proper.

These various sources of unsampled spawners and young may have been appreciable. However, inclusion of extra spawning grounds in the homing study would have raised the number of adults to be accounted for as well as the number of young fish marked.

The effect of these possible sources of non-sampled spawning on conclusions regarding homing to the inlet and outlet streams depends largely upon where such spawning occurred. That taking place in unsampled portions of Loon outlet or inlet streams would probably not alter homing conclusions, provided the numbers of trout utilizing non-sampled areas were not greatly different between inlet and outlet streams, and provided that homing behaviour of the sampled and unsampled components were similar. However, the same cannot be said for spawning in areas other than the outlet or main inlet. Homing to a small erratic inlet or to lake shoals may be greatly different than to the outlet or inlet. A large contribution of strays from these latter sources could seriously bias conclusions on homing to the outlet or inlet proper.

Considering the few adults which probably spawn each year in Thunder Creek it does not seem likely that strays to the outlet from this source could greatly affect the picture of outlet homing. Although local residents did not report the presence of shoal spawning in Loon Lake, nor was evidence of this observed during the study (1953–1958), there is no direct information available to preclude the possibility of its occurrence. Indirect information bearing on lake spawning may be obtained from an estimation of the total number of potential spawners in

Loon Lake compared with the number known or estimated to spawn in the outlet and main inlet each year.

The most reliable data for estimation of number of "catchable" trout in Loon Lake comes from the return to the lake of 1,175 adipose-clipped first spawners in the spring of 1954, and the subsequent recapture by anglers of 8 of these among a sample of 529 examined in a 1954 autumn angler census. This yields an estimate of 77,696 catchable trout in Loon Lake in the autumn of 1954. (Such an estimate neglects mortality of clipped fish between spring and autumn, but even if the *total* annual mortality occurred within this period, the estimate would not be lowered beyond 21,821). However, the estimate of 77,696 may be low because of incomplete mixing of marked trout throughout the lake, and restriction of the majority of angling effort to the outlet half of the lake. By assuming that all outlet clipped fish were restricted to the outlet half of Loon Lake, and weighting the sample for disproportionate angler effort on each half of the lake, an estimate of 94,881 catchable trout for the whole of Loon Lake is obtained.

Arguing from information on the relation between numbers of *catchable* trout in Paul Lake, B.C. (1932–1935) and numbers of spawners there (Mottley, 1949; Larkin *et al.*, 1950) a total spawning run of 30,358 trout in the outlet and inlet of Loon Lake in 1954 should represent a population of about 107,000 catchable trout in the lake. Therefore, the numbers of trout spawning in the outlet and inlet alone seem commensurate with that of the lake "catchable" population estimate, and would preclude the possibility of there being a *large* number of lake spawners in addition. In view of the above, it seems improbable that lake spawning, if present, would be appreciable enough to seriously alter conclusions on homing to the inlet and outlet of Loon Lake.

3. MARKING OF YOUNG FISH BY FIN CLIPPING MAY HAVE PRODUCED UNNATURAL MORTALITY.

Evidence for severe clipping mortality might be looked for in the proportion of small males spawning each year in the outlet. Drastic reduction in survival of the outlet fry and fingerlings clipped in 1953 and 1954 would have been reflected in a marked lowering of the proportion of small male spawners returning in 1954 and 1955. Actually this proportion rose appreciably rather than fell during 1954 and 1955. Evidence is, therefore, against there having been a clipping mortality sufficiently severe to be the sole explanation of the low proportion of adult clip recoveries. However the proportion of small fish both in the inlet spawning run (which would not have been much affected by large clipping mortality) and in anglers' catches from the lake, both showed large fluctuations from year to year. Therefore, it cannot be stated that clipping produced *no* extra mortality, as slight changes in the proportion of young spawning males due to this cause would have been obscured by the large natural yearly fluctuations. In any event, differential mortality would not be expected, amongst fish originating from one end, between those which homed and those which strayed. Therefore clipping mortality, if it occurred, probably did not seriously bias conclusions regarding degree of homing.

4. SOME FISH MARKED BY FIN CLIPPING MAY HAVE REGENERATED THEIR FINS SO AS TO BE OVERLOOKED AS RECOVERIES IN THE ADULT RUNS.

Considerable regeneration was observed in some fish which *were* detected as marked recoveries. Regeneration may have contributed substantially to the low number of recorded recoveries, particularly among fish marked when very small. This should not, however, seriously distort conclusions regarding homing, as markedly differential regeneration would not be expected between homers and strays originating from each end.

5. SOME YOUNG HATCHED IN THE OUTLET MAY HAVE ESCAPED THROUGH OUTLET TRAP 1 AND ENTERED THE LAKE WITHOUT BEING MARKED.

Entry of unmarked outlet young to the lake was probably appreciable only in June of 1954. During this high-water period Outlet Trap 1 was operated with coarse-mesh screening which allowed escape of small fish. Such escape occurred largely before the period of upstream movement of fry, and may account for the reduced proportion of fingerlings to fry in 1954

compared to the 1953 totals shown in Table I. This escape of fingerlings probably contributed to the discrepancy.

In conclusion, the discrepancy between the actual size of the outlet run and the calculated number of outlet spawners from one year's input of young to the lake, is probably due to a combination of the factors discussed above, most of which probably do not seriously alter conclusions reached concerning homing.

RETURN OF REPEAT SPAWNERS

From 1953 to 1955, a total of 3044 fish which had survived spawning in the outlet were marked (by tags or clipping) and returned towards the lake. Of these, 263 were subsequently recovered in 1954, 1955 or 1956 when they returned to the outlet and spawned for a second or third time. During these three years only a single former outlet spawner was found that had changed ends and was spawning next year in the inlet. These observations, based on examination of large samples of both outlet and inlet runs (15,853 and 23,046 fish respectively over the years) indicate an almost unerring tendency (99.6%) for fish which have once spawned in the outlet to return there for subsequent spawning. This "homing" is even stronger than the accuracy already shown (93.8%) with which fish hatched in the outlet return there for their first spawning.

No comparable calculation can be made for repeat spawning in the inlet, for of 3239 marked spent fish passed downstream through Inlet Trap 1 between 1953 and 1955, not a single fish was recovered spawning in subsequent years, either in the inlet or outlet. This is perhaps attributable to handling and marking of spent fish coupled with the greater rigours of the inlet stream; in it spawners must swim much farther, are in notably poorer condition after spawning, and presumably suffer higher natural mortality.

ADULT TRANSFER EXPERIMENTS

In 1955 a series of experiments was conducted to study the response of spawners to transfer from one spawning stream to the other at the opposite end of the lake. Thus in one type of transfer spawners which had entered the inlet stream were moved to the outlet, while in the other the outlet spawners were transported to the inlet stream. In each test about 50 adults caught in Outlet Trap 1 were marked by clipping half of the left ventral fin and were transferred to the inlet; a similar group caught in Inlet Trap 1 were marked by clipping half the right ventral fin and transferred to the outlet stream. Fish were transported by truck in several large cans, the operation requiring about 30 minutes. All inlet adults transferred to the outlet were placed between Outlet Traps 1 and 2 (Fig. 1) while approximately half the outlet fish transferred to the inlet were introduced about 200 feet upstream from Inlet Trap 1, and the remainder placed about 200 feet below this trap.

The results of five transfer experiments conducted between May and July are given in Table V. "New stream" refers to the stream to which the fish were artificially transplanted. Categories of behaviour following transfer are listed in a series ranging from complete conformity to the new stream (i.e. spawning there

TABLE V. Results of adult transfer experiments, Loon Lake 1955.

Type of transfer	Outlet to inlet		Inlet to outlet		
Date of transfer	4 May	12 May	4 May	19 May	12 July
Number transferred, males	20	21	23	23	34
" " , unripe females	22	0	18	19	15
" " , ripe females	8	27	5	6	23
Spawned in new stream, then moved towards lake	7	0	2	0	0
Spawned in new stream, then moved away from lake	2	4	3	0	3
Returned to original stream; spawning condition not known	4	3	4	1	0
Returned to original stream; still ripe when observed	12	0	1	1	0
Returned to original stream; spent when observed	1	1	2	0	0

and then returning towards the lake) to complete rejection of the new stream (i.e. returning to the old stream and presumably spawning there). Only individuals definitely falling into one of the listed categories are included.

Some flooding occurred at Inlet Trap 1 from May 5 to May 21, and at Outlet Trap 1 from May 16 to May 27. During these periods it was possible for some transferred fish to move past the traps unrecorded, but both traps acted as samplers of fish movement even during flood periods, and provided complete counts at other times.

Females used in the transfers were classified as "ripe" or "unripe" depending on whether or not a few eggs could be extruded by light pressure on the abdomen. The proportion of ripe to unripe females rose in successive experiments. Table V shows that, in both types of transfer, when relatively few fish were ripe more of them rejected the new stream and returned to their original stream than was the case when the majority were ripe. Thus with transferred outlet adults 17 out of 50 returned to the outlet following the May 4 transfer (when few females were ripe), while only 4 out of 48 were recovered in the outlet following the May 12 transfer (when all the females were ripe). Likewise with transferred inlet adults, 7 out of 46 returned to the inlet following the May 4 transfer when few females were ripe, while no returns to the inlet were recorded after the July 12 transfer when the majority of females were ripe. The relation between acceptance of the new stream and advancing season (and ripeness of females) is evident despite disproportionate sampling as a result of flooding traps.

Considering only transfers made when few fish were ripe, a comparison of behaviour following transfer may be made between outlet and inlet transfers. The two-way transfer of May 4 indicates that in both cases at least some of the transferred adults remained to spawn in the new stream. However, a larger proportion of outlet fish returned to their original stream (17 out of 50) than was true for

inlet fish (7 out of 46). The inlet to outlet transfer of May 19 when few females were ripe also shows a low return of inlet fish (2 out of 48).

When a large proportion of the transferred fish were ripe (May 12, July 12) returns to original streams were low, but even then at least 4 of the 48 outlet adults returned to the outlet, while no inlet adults were recovered again at the inlet. Trap operation at the inlet trap at this time permitted examination of all fish ascending there. There is a good indication, therefore, in these data that return to original stream following transfer is more effective with outlet adults than with inlet adults.

MOVEMENT OF FISH WITHIN LAKE

Capture of marked juvenile and adult fish in Loon Lake by anglers provides information on lake movement of two groups of fish: (a) those originating in the inlet or outlet and moving into the lake as fry or fingerlings and (b) those spawning in the inlet or outlet and subsequently returning to the lake.

Large numbers of clipped fry and fingerlings entered Loon Lake during the spring and summer of 1953 from inlet and outlet streams of Loon Lake (Table I). Clipped fingerlings were first captured by anglers in 1954, while fish marked as fry and fingerlings were taken in 1955 and 1956. Angler recovery of these fish is summarized in Table VI.

TABLE VI. Recovery of clipped fish from anglers' samples.

Year	Section of lake	Total number sampled	Outlet clips		Inlet clips	
			Number	Percent	Number	Percent
1954	Outlet	1064	15	1.41	1	0.09
	Inlet	181	1	0.55	0	0
1955	Outlet	715	37	5.17	3	0.42
	Inlet	325	8	2.46	3	0.92
1956	Outlet	678	5	0.74	0	0
	Inlet	298	5	1.68	0	0

Fish marked as young in the outlet were recovered in greater numbers by anglers than were inlet fish. This is a reflection of larger numbers of outlet fish marked and also more intensive angling and sampling of anglers on the outlet half of Loon Lake. Although outlet fish appear to occur in greater numbers in the outlet half of the lake in 1954 and 1955, the situation was reversed in 1956 when a greater percentage of outlet fish occurred in the catch from the inlet half of the lake. Amongst inlet fish taken by anglers in 1955, a slightly higher percentage occurred in the inlet than in the outlet halves of the lake. Young trout originating from one end of Loon Lake evidently do not remain exclusively in that end during their period of growth.

Some of the adults spawning in the inlet and outlet were marked by tags or clips in 1953 and 1954. A number of these marked adults were subsequently caught in the lake by anglers or were recaptured in stream traps at the end of the lake opposite to that where they were originally marked.

In 1954 a large number of inlet spawners were marked, either ascending or descending at Inlet Trap 1, by removing half the right ventral fin. During the marking period 101 of these fish which had been marked in the inlet were recovered at Outlet Trap 1. Many of these fish were dead when recovered and the majority were in poor condition. At the beginning of the marking period it was possible to identify individual fish recovered at the outlet on the basis of sex and length. One

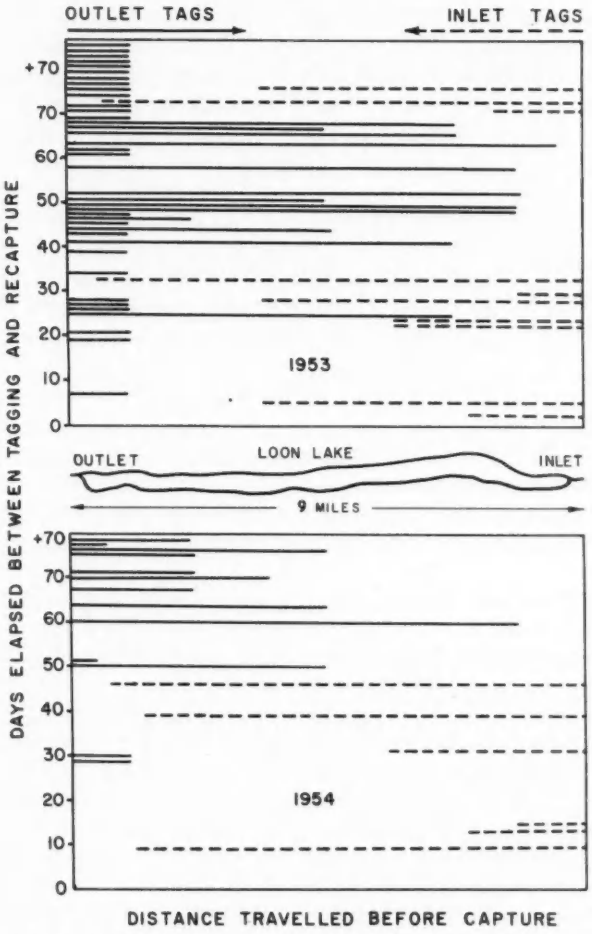

FIG. 4. Dispersal of spent adult rainbow trout within Loon Lake, as indicated by tag recoveries in angler catches.

female taken in the outlet on June 24 at 10:00 hours had been clipped at the inlet on June 22 at 12:00 hours, and had thus made the journey from inlet to outlet stream, passing through the entire length of the lake, in a maximum of 46 hours. The fact that 101 clipped inlet adults made their way to the outlet after spawning would suggest that at least inlet adults which return to the lake after spawning make extensive movements throughout the lake. Handling and clipping fish of course may have in some way altered their behaviour.

Additional information on movement of adult spawners following return to the lake is available from angler recapture of tagged fish. In 1953 anglers took 43 tagged outlet adults and 10 tagged inlet adults in the lake; in 1954, 13 outlet and 10 inlet adults were caught. The approximate site of capture within the lake is shown for inlet and outlet tagged adults on both years in Fig. 4. The majority of outlet fish were recaptured in the outlet half of Loon Lake, while inlet fish were taken in about equal numbers in the two halves. A more intensive fishery operating on the outlet half of Loon Lake probably accounts for the majority of outlet fish being caught there. In general fish which were taken in the section of the lake opposite the end at which they were tagged had spent more than 20 days in the lake. Recovery of these adults by anglers shows that they do not necessarily remain near the stream from which they returned to the lake, and many make extensive movements within the lake.

In summary, recoveries by trapping and by anglers of clipped and of tagged fish all suggest considerable mixing throughout the lake, rather than the existence of discrete populations associated with either end.

MORPHOLOGICAL EVIDENCE FOR HOMING

Evidence for non-random assortment of spawning adults between Loon Lake inlet and outlet may be gained from counts of meristic and other morphological characters on trout from each stream. Samples of adult spawners and young taken at Outlet Trap 1 and Inlet Trap 1 in 1953 were preserved in formalin and counts made later of pyloric caeca, scales along the lateral line, and total vertebrae (Table VII).

Inlet spawners had significantly more pyloric caeca than outlet spawners.

TABLE VII. Morphological data for adult rainbow trout from outlet and inlet spawning streams of Loon Lake in 1953.

Stream		Pyloric caeca	Lateral line scales	Total vertebrae
Outlet	Mean and S.E.	50.48±0.68	155.52±0.90	63.12±0.14
	Sample Size	85	48	68
Inlet	Mean and S.E.	52.73±0.69	150.94±0.96	63.04±0.15
	Sample size	86	49	70
Difference		−2.25±0.97*	+4.58±1.31**	+0.08±0.21

*Significant at $P < 0.05$
**Significant at $P < 0.01$

A similar comparison between caecal counts of young fish (fry and fingerlings) from the two streams yielded ambiguous results due to large variability between samples collected at different times and under different circumstances.

Outlet spawners had significantly more lateral line scales than inlet spawners. Numbers of lateral line scales were not counted in young as most inlet young and many outlet young do not form scales until they take up lake residence.

No significant differences were evident in total vertebral counts between inlet and outlet spawner samples. Vertebral counts were not made on young trout.

Significant differences in morphological characters (pyloric caeca and lateral line scales) found between adults spawning in inlet and outlet streams offer independent evidence that adults do not select their spawning stream at random. These morphological differences are not necessarily of genetic origin but may be a result of environmental differences in the two streams during development, as Tåning (1952) has shown that temperature during development is capable of altering meristic counts in *Salmo*.

DISCUSSION

Considerable evidence indicates that in the inlet and outlet of Loon Lake, trout behave, in each stream, in a manner appropriate to their successful reproduction there. From the inlet almost all the young pass *downstream* into the lake in their first year. In the outlet, evidently few fish are lost from the system through downstream movement; instead, they move *upstream* in either their first or second year and so enter the lake. As adults, trout enter both inlet and outlet in large numbers to spawn, and those surviving after spawning usually return in the appropriate direction to regain the lake.

The problem was raised in the Introduction whether these differences in behaviour, which are apparently nicely attuned to inlet or outlet reproduction, are due to the presence of two genetically distinct types of fish, or instead to environmental differences between the two areas which produce opposite reactions in genetically similar fish.

If the explanation lies in two genetically distinct types of fish, then there should be virtually complete homing of inlet-hatched fish to the inlet and of outlet-hatched fish to the outlet. Even a moderate amount of straying in each generation would be sufficient to eliminate genetic distinctness between each homing population, unless most progeny of each stray were lost from the system through inappropriate current response. Several years' trapping data indicate almost no movement of young fish in the "wrong" direction (other than during rare periods of exceptional environmental conditions).

All available evidence is against the existence of two genetically distinct types of fish in Loon Lake. The recovery as "strays" of 20 marked adults spawning in the stream in which they were *not* hatched is direct evidence for genetic interchange. Estimates of the composition of both spawning runs suggest that each year about 6% of all spawners are strays. Because of the marked difference in size of spawning runs to inlet and outlet streams of Loon Lake, even a low percentage

of straying of young which originated from the large inlet spawning population results in about a quarter of the smaller outlet run being composed of inlet strays.

Moreover, it has been demonstrated by transfer experiments that behaviour patterns of adults with respect to current are not unalterably fixed. In these experiments some individuals when transferred to the "wrong" end spawned there and then moved towards the lake.

Recoveries of marked fish in the lake also suggest that fish entering the lake either as young or as spent spawners do not remain as discrete populations, but instead gradually spread and mix.

Experiments have been conducted, both in the field and the laboratory, on factors governing the direction of movement of young in both inlet and outlet streams. Two-way transfers of fry between Loon inlet and outlet (not described in this paper) have shown that young from these two sources do *not* have innate opposite current responses characteristic of the stream in which they hatched, but rather behave in a manner appropriate to the stream to which they are transferred. Direction of movement is apparently controlled largely by a combination of environmental factors, including temperature and light (although the possibility of some innate behavioural difference has not been disproven).

All the foregoing lines of evidence indicate that behavioural differences of fish in the two streams are largely determined environmentally rather than genetically. This is not to say that there are not some slight average hereditary differences between trout spawning at the two ends. Those meristic differences found between inlet- and outlet-spawning adults might have a partially genetic and partially environmental origin (as was demonstrated for Kootenay Lake kokanee *Oncorhynchus nerka* by Vernon, 1957). Homing tendency coupled with differential survival at the two ends could maintain small mean differences in the genetic composition of inlet and outlet spawners. However, the opposite current reactions of both young and adults can scarcely be attributed to innate differences, for the reasons outlined above.

While perfect homing and genetic discreteness do not occur, the choice of spawning streams by trout in Loon Lake is very far from random. A strong tendency to "home" has been demonstrated, in fish hatched in the outlet as well as the inlet; in each case homing appears to be about 94% effective.

Some attention has been devoted, in this paper, to alternative methods of expressing the extent of homing. Ideally this should be given as the number of homers in relation to the *total* number of spawners, both homers and strays, which originated from a given stream. However, unlike the present experiments, many studies on homing cannot completely sample all spawning sites which might contain strays from the parent stream. Anadromous species offer outstanding difficulties in this respect. The Loon Lake study offered an unusual opportunity to compare different methods of expressing homing. Although in this instance the various methods of calculation did not yield radically different results, they demonstrate that reliance on incomplete sampling of all spawning areas may give a misleading measure of homing. In particular the relative sizes of runs to each stream must be considered. For example, if equal sized samples from Loon Lake inlet and

outlet were separated into homers and strays, with no cognizance taken of the fact that the inlet run is much larger than the outlet, then it would be concluded erroneously that straying was much greater amongst fish originating from the inlet.

All calculations in this study are based on a synthesis of events over several years. Survival of young is known to fluctuate considerably from year to year, as evidenced by large annual differences in stream flow and in age composition of spawning runs and anglers' catches. Consequently, the figures in Table IV and Fig. 3 should be taken only as approximating the "average" situation. Degrees of straying amongst inlet- and outlet-reared fish, although almost indentical according to present calculations, are not necessarily so in all years. Moreover, the size of spawning runs to the two ends may vary appreciably in different years. However, the relative magnitudes of the runs probably do not alter, and the calculations present a satisfactory picture of homing and straying, in general outline though not necessarily in detail.

In the type of homing and straying depicted in Fig. 3, equilibrium over successive generations can be preserved only if reproductive success is slightly lower amongst outlet spawners than amongst inlet spawners. (Otherwise, the regular contribution of a larger total number of strays from inlet to outlet than in the reverse direction would gradually equalize the sizes of the two runs.) A slightly lower survival in the outlet may be due to predation on fry and fingerlings which are confined in the shallows of the outlet stream for a protracted period. Predators in the outlet are known to include mink, kingfishers, and yearling trout which are large enough to eat trout fry (Hartman, 1958).

The mechanism whereby trout in Loon Lake locate their home stream is unknown. Strong evidence of the ability of fish to orient by means of extremely dilute odours has been presented by Hasler and Wisby (1951). Mitigating somewhat against odour orientation in the present case is the fact that fish homed equally to an inlet and to a stream flowing out of the lake. Possibly, in the relatively limited area of a lake, fish learn to orient also according to visual and spatial clues around the stream mouth, perhaps reinforced by successive visits.

If spawners home by recognition of the appropriate stream mouth, then return by some of the artificially transferred adults to their stream of first capture requires further explanation, as these fish were placed in the new stream well beyond its mouth. Sun-orientation, demonstrated in certain fishes by Hasler *et al.* (1958), is probably not involved in the present experiments because the fish were transferred in covered cans.

One interpretation of the behaviour of these individuals might be that, despite transfer, they simply continued moving in the same current direction they had been following before capture. Thus fish moving downstream when captured in the outlet continued to do so after release in the inlet. Upon reaching the lake they then relocated and re-entered the outlet as before. Conversely fish transferred to the outlet continued the upstream course they had been following when taken in the inlet, and so regained the lake. Perhaps in late transfers involving near-ripe fish, many individuals acquired a necessary degree of ripeness coincident with the presence of appropriate spawning facilities in the new stream, and hence spawned

there. (This is consistent with the greater return by fish transferred to the relatively cold inlet than by those transferred in the reverse direction. Greater return of this group may also have been enhanced by passive downstream transport, particularly if they were exhausted by handling.) The principal assumption in this interpretation of the transfer experiments is that the direction of swimming with respect to current was fixed once a spawner entered either stream. This could conceivably be a rapidly-learned current response such as shown for young migrant Pacific salmon by Hoar (1958). These conjectures are included to demonstrate that return of some transferred adults does not preclude the possibility that the initial clues used in "homing" might still involve only recognition of the mouth of the home stream.

In addition to the problem of how adults locate their home stream, there remains the question of what determines the time of their entry into the chosen stream. Evidently most outlet-hatched fish enter their home stream and spawn earlier in the year than do most inlet-hatched fish. However, selection of spawning stream by each fish is probably not dictated solely by the time of onset of sexual maturity; the first spawners taken in the inlet traps each year were distinctly "green", at a time when the late entries into the outlet had ripe and free-flowing eggs. Nor was there evidence of a larger proportion of inlet strays in the late portion of the outlet run.

It may be hypothesized that all fish in the lake require that the temperature rise above a certain threshold (averaging about 5°C) before they will enter a spawning stream. When the outlet temperature rises above this threshold, usually early in April, outlet-hatched adults, which have located the outlet (perhaps by visual or olfactory clues) begin to move into that stream. Variation in time of arrival might be due in part to variation between individuals in reaching the necessary sexual condition, and in part to the fact that some fish are late in arrival because they were in a remote part of the lake in early spring. The riper condition of late entrants into Outlet Trap 1 may be due to the much higher water temperature in the stream mouth towards the end of the outlet run.

According to this hypothesis, most inlet-hatched fish which happened to be in the vicinity of the outlet would fail to enter it, despite the suitable temperature, because the stream lacked the necessary unknown "home" clues. At the same time, inlet-hatched fish might congregate off the mouth of the inlet stream but would not enter until its temperature rose above the acceptable threshold. Strays to either end might be fish insufficiently endowed with homing clues to overcome the attractive force of suitable temperature, current etc. in the wrong stream within whose influence they accidentally strayed.

The foregoing picture is conjectural, but it fits the available evidence. An alternative hypothesis might be that outlet-hatched fish mature somewhat earlier in the season than inlet-hatched fish, and simply enter the first stream which attains a high enough temperature. It is true that outlet young have a "head start," over inlet young of at least several weeks in their first year, because of earlier egg deposition and hatching, higher temperature and faster growth in the outlet stream. On the other hand, this head start would have to produce early sexual development

in all fish of each-class, including some reaching first maturity at age III, some at age IV and some at age V. The almost unerring return of outlet second spawners to their site of first spawning would also be unexpected, if choice of spawning stream depended on state of sexual development. Moreover, lack of evidence of a higher proportion of strays in the late segment of the outlet run argues against sexual state determining the choice of spawning stream. The case against there being large genetic differences between fish spawning in the two streams (which might control time of maturation) has already been argued.

In summary, homing seems best attributable not to choice of whichever stream has suitable temperature at time of sexual maturation, but rather to an active selection by most fish of the stream of their own hatching, using learned clues of an unknown type.

Homing of salmonids, well known amongst anadromous forms (Taft and Shapovalov, 1938; Scheer, 1939) has also been demonstrated for non-anadromous forms in other lakes. Vernon (1957) showed that kokanee homed to inlet spawning streams in three areas of Kootenay Lake, with less than 3% straying. Stuart (1957) showed that brown trout (*Salmo trutta*) also homed strongly to specific inlet spawning streams entering a Scottish reservoir.

Probably a moderate tendency to home is not uncommon in fishes, both land-locked and anadromous. From the point of view of successful reproduction of the individual, homing serves to ensure that eggs are deposited in an area capable of rearing the young. (Innate requirements for "releasers" such as suitable gravel-size, water flow, etc., also serve this end, but cannot ensure the progeny against later dangers which might be regularly associated with a stream, such as lowered flows, lethal temperature, or heavy predation on fry.) From a more general viewpoint, homing in a species tends to balance the number of spawners using each stream against the reproductive capacity of the area. At the same time, some straying must also have a long-term selective advantage, enabling the species to invade new areas and to repopulate old ones in the wake of local catastrophes.

The term "homing" has been variously used, to mean return by an animal to its usual place of habitation, or even "the compulsion of an individual to return to a specific locality" (Platts, 1959). Such usage would include territoriality and other phenomena not necessarily associated with reproduction. Our use of the term here is restricted to mean the return of an animal, prior to reproduction, to the place of its own genesis. This phenomenon might be called "reproductive homing". Many studies which have depended on marking of adult animals and their subsequent recapture could not be said to deal directly with this type of homing, as they do not yield evidence on the fundamentally important question of genetic continuity between successive generations of a population.

The degree of homing of trout demonstrated in the Loon Lake study, although insufficient to explain inlet and outlet behaviour differences on a genetic basis, is nevertheless sufficient to be of significance to fisheries management for other reasons. The inlet and outlet populations must be treated as semi-discrete in applying management techniques. Loon Lake, and several similar heavily populated trout lakes in British Columbia with inlet and outlet spawning, have been

used for collecting eggs for hatcheries. Because fish do not assort at random between inlet and outlet, repeated removal of all eggs from one stream will result in marked depletion of the run to that stream. For example, it could be predicted that continued removal of all eggs from the outlet run of Loon Lake would result in eventual reduction of the number of spawners there to about one quarter, while removal of all eggs from the inlet run would virtually obliterate that run. Angling in Loon Lake is most concentrated towards the outlet end; severe depletion of the outlet run would have a disproportionate impact on the fishery, because outlet offspring leaving or entering the stream are most concentrated where angling is heaviest. This type of consideration of semi-discrete homing populations is probably relevent to fisheries management problems in many other lakes.

Because the degree of homing demonstrated in this study is not precise enough to allow the existence of two genetically discrete populations, the explanation of behavioural differences between inlet and outlet presumably lies in some environmental differences between the two ends. Further studies now in progress suggest that several environmental factors may in combination vary between inlet and outlet streams in such a way as to produce in young trout the behaviour appropriate to that environment.

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A Concept of Growth in Fishes[1,2]

By Robert R. Parker[3] and Peter A. Larkin[4]

ABSTRACT

The use of size as a basic determinant of growth rate is discussed and compared to analogous situations described in literature on other physiological rates. *Ecological* opportunity and *physiological* opportunity are visualized as the two interacting components that determine growth, both of which are entered at "threshold" sizes. The parabolic function,

$$dw/dt = kw^x$$

is developed into a growth equation for linear dimensions and its application explored and discussed using steelhead trout and chinook salmon as an example. Significant differences in growth rate are found between life history types and sexes. The chinook data are then treated on a l_{t+1}, l_t plot and it is shown how an apparent fit of the von Bertalanffy type growth equation can result from selectivity of fishing for the larger fish of any brood year. Two lines of research are indicated. (1) The independent measurement of the exponent x through study of size-specific metabolic rates, and (2) the relationship between total mortality rate and growth rate. Without this knowledge a satisfactory synthesis of growth rate into a yield equation cannot be achieved.

INTRODUCTION

Prediction of growth in natural populations of fishes is an important facet of many applied problems of fisheries management. As a first approximation it might be expected that age would be an adequate criterion of size and growth potential. However, it is well known that rates of growth of fishes are influenced by environmental conditions such as relative abundance of food and relative density of population. Age is thus only a reliable index of size or growth rate in relatively constant environments. However, even under a given set of physical conditions opportunity for growth of the individual fish may not be related to age. Brown (1946), Stringer and Hoar (1955), Newman (1956), and Kalleberg (1958) describe size hierarchies in groups of fishes which influence their growth rates. Larkin, Terpenning and Parker (1957) suggest that size gives a better indication of *ecological opportunity* for growth than does age in rainbow trout (*Salmo gairdneri*). They also suggest size "thresholds" which, when crossed, provide the individual with new growth opportunities.

Physiologists have long recognized that size is the better criterion of *physiological opportunity* for growth. Brody (1937, 1945) indicates that chronological age may not reflect physiological age. Pütter (1920), Brody (1945) and von Bertalanffy (1938) developed growth equations in which size and the difference between size and an "ultimate size" determines the growth rate.

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These equations have been applied to studies of natural populations of fish (Beverton and Holt, 1957). However, there are instances in which growth of fishes is not adequately described by these systems (Ricker, 1958). Some fish do not appear to be growing to an "ultimate size". Many species may change their ecological niche as they grow larger, thus revising the "ultimate size" to which they are growing (Larkin, Terpenning and Parker, 1957). Many species of salmonoids undergo marked physiological transformations (Hoar, 1939, 1950, 1957; Green, 1926; Mislin, 1941) at different periods of their life history and these transformations may also be related to a size "threshold" (Alm, 1949; Elson, 1957; Parry, 1958). Growth of fish may thus be visualized as a series of growth stanzas (Brody, 1945) which are entered by ecological and physiological size thresholds, and within which size is the basic determinant of both ecological and physiological opportunity for growth.

The question of mathematical technique for describing growth is highly controversial. Arbitrary curve fitting may result in growth equations which combine dissimilar growth stanzas, thus "smooth out" important aspects of growth processes. *Within* each growth stanza, curves of "best fit" may result in growth equations in which the constants have no biological meaning or at best are of vague and complex significance (Gray, 1929). Alternatively, if equations are used which have been derived from physiological premises (and for which presumably the constants have physiological meaning) there is the risk that the empirically determined values of these constants will reflect the combination of physiological processes with other factors influencing growth in natural environments, hence will not actually describe accurately the physiological processes from which they were deduced. Under such circumstances it would seem appropriate to choose a method of depicting growth which (1) summarizes the complex of interacting factors in each stage of growth into a minimum number of constants which reflect the combined effects of both ecological and physiological factors, (2) chooses as a basic premise the widely accepted view that change in size is a function of size achieved.

Assuming that size is the basic determinant of growth the simplest mathematical expression to describe growth would be

$$dw/dt = f(w) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where growth rate (w/t = weight/time) is some function of weight attained.

A first approximation containing one variable is

$$dw/dt = kw \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

i.e., exponential growth as derived from Minot's (1891) growth equation by Brody (1927). Since growth in weight is rarely observed to be exponential, a modified function involving two variables is

$$dw/dt = kw^x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where k establishes the coordinates of the system and x is a fractional exponent of weight less than unity.

This type of equation appears a particularly suitable choice because it parallels empirical description of the relationship between weight and various physiological processes. In these instances also, the mechanisms involved may be complex and incompletely understood but the mathematical expression adequately describes the end result. For example, it has been abundantly demonstrated (Brody, 1945; Adolph, 1949) for mammals that standardized physiological rates are related to size and can be adequately represented by the parabolic equation

$$dR/dt = Aw^x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3a)$$

where dR/dt denotes a physiological rate and A is a proportion constant. Why equation (3a) should adequately represent so many body functions is not understood (Weymouth, Field and Kleiber, 1942; Pirozynski and von Bertalanffy, 1951; von Bertalanffy and Pirozynski, 1953; von Bertalanffy and Estwick, 1953, 1954) but it is well established as empirical fact through many observations. As far as they have been studied, equation (3a) also describes physiological rates for fish, viz.: oxygen uptake under standard resting conditions and under active conditions (Fry, 1957; Job, 1955), oxygen uptake being interpreted to indicate metabolic rate.

The present study has as a main objective the description of growth of fishes, using the theoretical premise that growth rate may also be described by a parabolic equation. This possibility has apparently not been previously explored in the study of growth of fish, although Kleiber (1947) suggested that gain in weight of farm animals should be related to the ¾ power of weight.

MATERIALS

Steelhead trout (*Salmo gairdneri*), the anadromous form of rainbow trout, and chinook salmon (*Oncorhynchus tshawytscha*), offer an opportunity for study of the growth problem. They have highly variable life histories (Maher and Larkin, 1955; Parker and Kirkness, 1956; see Wilimovsky and Freihofer, 1957, for entrance to literature on chinook), and show greatly differing growth rates in their freshwater and marine environments. Accordingly, fish of several ages and life history patterns but of the same size can be compared in similar environments at the same time.

Material for this study was selected from data described for Chilliwack River[5] steelhead by Maher and Larkin (1955) and for chinook salmon[6] by Parker and Kirkness (1956). The steelhead used were all mature. The chinook sample contained some immature specimens, however the sample as a whole was calculated to include more than 80% of fish in their ultimate year of life (Parker and Kirkness, 1956), and were of mixed racial origin. All original measurements were in inches fork length.

[5]A tributary of the Fraser River 60 miles above salt water, in British Columbia.
[6]Of mixed origin caught by commercial troll off the coast of Southeastern Alaska between Sitka and Cross Sound, 57° to 58°N Lat.

Length at age was calculated from scale measurements by direct proportion. For steelhead the dorso–ventral diameters of scale, and scale annuli were used. The use of direct proportion back calculation seemed justified for this species from the findings of Smith (1955) and of Mottley (1942). Direct proportion between fork length and anterior radii of scale and scale annuli was assumed for chinook. Preliminary examination of this assumption was made using a sample of 93 chinook selected to provide maximum range in size (18.5 to 41.0 inches). The equation $Y = ax^b$ was fitted to the regression of anterior scale radius (Y) on fork length (x). In log form the regression was obviously linear, with slope: $b = 0.9731$, $s_b^2 = 18.0863 \times 10^{-4}$. If b is tested against unity, $t = 0.63$, d.f. 91, $0.6 > P > 0.5$. Accordingly the use of direct proportion for back calculating length at age of chinook should not introduce serious error.

All data were selected to conform to the following criteria: 1. Scale margins were clearly defined, showing no apparent resorption of scale margins associated with sexual maturity. 2. Steelhead used were "first spawners", eliminating any error in back calculation from scale resorption of a previous spawning. 3. Steelhead were fish which had gone to sea during the early spring. The "fall migrants" of Maher and Larkin were eliminated. Freshwater growth of chinook was not considered in the present analysis. 4. Scales used were regularly shaped, and without apparent previous damage or regenerated parts. 5. All individuals completed the last annulus in the 1949 or 1950 growth year. A growth year is here defined as that portion of life history bounded by the completion of two adjacent annuli. 6. Growth in the year of maturity is not considered in the present analysis. 7. Chinook used were restricted to the "ocean type" (Fraser, 1917; Rich, 1925), i.e. those fish that migrated to the sea before the formation of the first annulus.

TABLE I. Life history of steelhead and chinook used in growth analysis.

Species	Life history type	Sex ♂	Sex ♀	Total number of fish
Steelhead	2/1	20	21	41
	2/2	21	31	52
	3/1	22	25	47
	3/2	4	8	12
	Total:	67	85	152
Chinook	0/2			27
	0/3			150
	0/4			60
	0/5			8
			Total:	245

The "life history type", or combination of freshwater and salt water annuli on the scales of each fish, is indicated as, for example, 1/3, which denotes 1 annulus in freshwater and 3 in salt water, etc. Table I presents the data used in the present study grouped according to sex (steelhead) and life history types.

MATHEMATICAL DERIVATION

The basic relationship describing growth in mass is taken as

$$dw/dt = kw^x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Integrating (3):

$$\int_{w_0}^{w_t} w^{-x} dw = k \int_0^t dt$$

$$w_t^{(1-x)} = (1-x)kt + w_0^{(1-x)} \quad (4)$$

Since there is no knowledge of size except at the completion of each annulus, t must be considered in whole units of one year each. If we set $t = 1$, i.e. only consider growth from time t to $t + 1$, the relationship becomes a regression of $w_{t+1}^{(1-x)}$ on $w_t^{(1-x)}$, with intercept $k(1 - x)$ and slope always equal to unity, thus:

$$w_{t+1}^{(1-x)} = k(1-x) + w_t^{(1-x)} \quad (5)$$

Equation (5) holds for all values of w_t without regard to absolute age.

Assuming the weight–length relationship to be adequately described by the expression:

$$w = ql^y \quad (6)$$

and substituting for w in (5), the general equation in terms of length becomes:

$$l_{t+1}^{y(1-x)} = \frac{k(1-x)}{q^{(1-x)}} + l_t^{y(1-x)} \quad (7)$$

which may be denoted as:

$$l_{t+1}^z = \alpha + l_t^z \quad (8)$$

where:

$$\alpha = \frac{k(1-x)}{q^{(1-x)}}$$

$$z = y(1-x)$$

Graphically if l_{t+1}^z is plotted on the ordinate and l_t^z on the abscissa, points formed from a length progression l_1, l_2, l_3, etc. will lie α distance above a 45° diagonal originating at 0, 0. Thus α expresses length increment in a manner which is comparable regardless of size or age. It thus has the same utility as instantaneous relative growth rate would have in the case of an animal growing exponentially[7] (equation 2).

[7]Exponential growth (Brody 1927, 1945) is a limiting case of (3) where:

$$dw/dt = kw^{x-1}$$

and the axes are transformed by logarithms.

Some characteristic curves (for relationships characterized by values of $z = 0.5, 1.0, 1.5$) are plotted on unmodified axes in Fig. 1. Two of the curves, $l^{0.5}$ and $l^{1.5}$ represent extremes that have been met with by the authors. Thus in

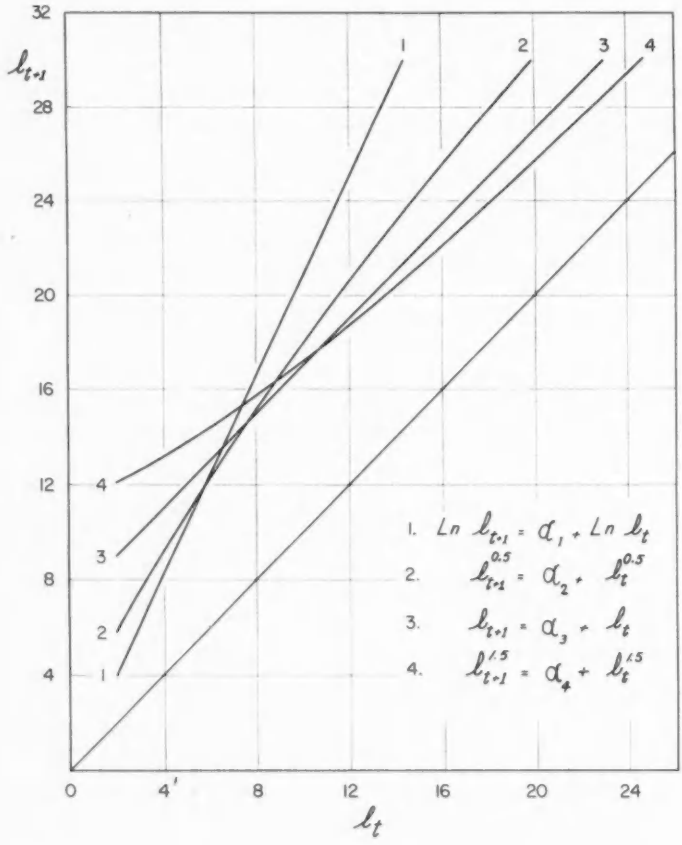

FIG. 1. Plot of l_{t+1} on l_t for hypothetical fish growing from 2 to 30 units (length) in 4 years, using different exponents (z). Line No. 1 represents exponential growth.

plotting l_{t+1} against l_t, if the trend appears to diverge from the 45° diagonal, the value of z probably lies between 0.5 and 1.0. Conversely, if the data appear to approach the 45° diagonal, z is likely to lie between 1.0 and 1.5. If the data appear linear and parallel to the diagonal, the value of z will be close to 1. Assuming no

progressive change in shape (isometry), weight may be described by the equation:

$$w = ql^{3.0}$$

and the corresponding differentials for growth are as follows:

$$z = 0.5,\ dw/dt = kw^{5/6}$$
$$z = 1.0,\ dw/dt = kw^{2/3}$$
$$z = 1{\cdot}5,\ dw/dt = kw^{1/2}$$

Since in (8) both α and z are presumably unknown, z is found using trial values and seeking a minimum relative variance of α.[8]

If a computer is unavailable the tedium of determining z may be considerably reduced in the following manner. Length at previous age data (l_1, l_2, l_3, etc.) are transformed to $l_1^{0.5}$, $l_2^{0.5}$, $l_3^{0.5}$ etc. and $l_1^{1.5}$, $l_2^{1.5}$, $l_3^{1.5}$, etc., giving three sets with z values of 0.5, 1.0, and 1.5, respectively. For each set compute mean α ($\bar{\alpha}$) and its variance (s_α^2). The square root of the relative variance $\left[\frac{s_\alpha^2}{\bar{\alpha}^2}\right]^{\frac{1}{2}}$ or relative standard deviation, s_R, was found to be related to z approximately as a quadratic function:

$$s_R \approx a + bz + cz^2 \tag{9}$$

Having three sets of values of s_R and z, (9) can be solved using simultaneous equations. Optimum z (the value of z giving minimum relative standard deviation) is obtained when the derivative of (9) is zero, thus:

$$2cz + b = 0; \qquad z = -\frac{b}{2c} \tag{10}$$

This method has given values of optimum z accurate to two places.

A graphic approximation can also yield usable estimates of both z and α. As stated by Brody (1945), the eye is quite sensitive to deviations from a straight line and if data are rectified by suitable alteration of the axes linearity will be apparent. Scales for converting axes for z values of 0.1 to 2.0 are presented in Fig. 2. Graph paper can be made using these scales, length data converted to a hundred-unit scale (so all length values are more than one and less than 100) and plotted directly as l_{t+1} on l_t. A straight line fitted by "eye" to the data and with a slope of 45° can be used to judge goodness of fit.

For best accuracy, in lieu of a computer, it is suggested that the treatment of data be first approached graphically, then solved by use of the quadratic method, choosing two values to bracket and a third to approximate the desired optimum.

With an optimum value of z the length-at-age data are then converted to l_1^z, l_2^z, l_3^z, etc. Significance of differences in growth between any desired groupings, or populations, can then be decided using analysis of variance on the α values for individual fish.

Certain precautions are necessary when determining z for any group of data. When l_{t+1} is plotted against l_t a single point, representing growth as vertical

[8]An ALWAC III-E computer was used. The program is on file at the Computing Centre, University of British Columbia, Vancouver, Canada. Copies may be obtained by request.

distance above the 45° diagonal is obtained. At optimum z, growth is given as $\bar{\alpha}$, an abstract unit, which is an appropriate statistic for all sizes and/or ages provided the assumption of steady state environmental and physiological conditions

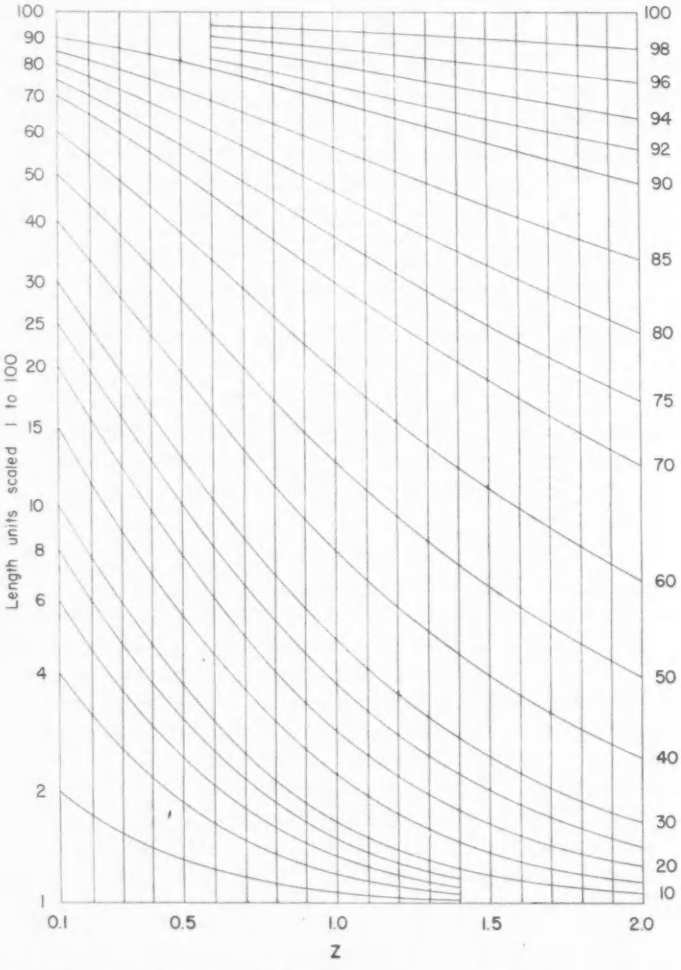

FIG. 2. Nomograph for establishing axes in making graph paper with l^{α} scales.

is approximated. However, natural variation in ability to grow (genotypic) as well as variation in growth dictated by environmental opportunity and social interaction (phenotypic) is typical of fish populations. To some degree fast-growing individuals and slow-growing individuals maintain their relative status throughout life. For any group of fish in which all l_t values are close, i.e. in the

same order of magnitude, a line of best fit with co-ordinates l_t, l_{t+1} will vary more or less from a slope of 1, if the relative size position of fish in a population tends to remain stationary. Under these conditions a fast-growing member is always

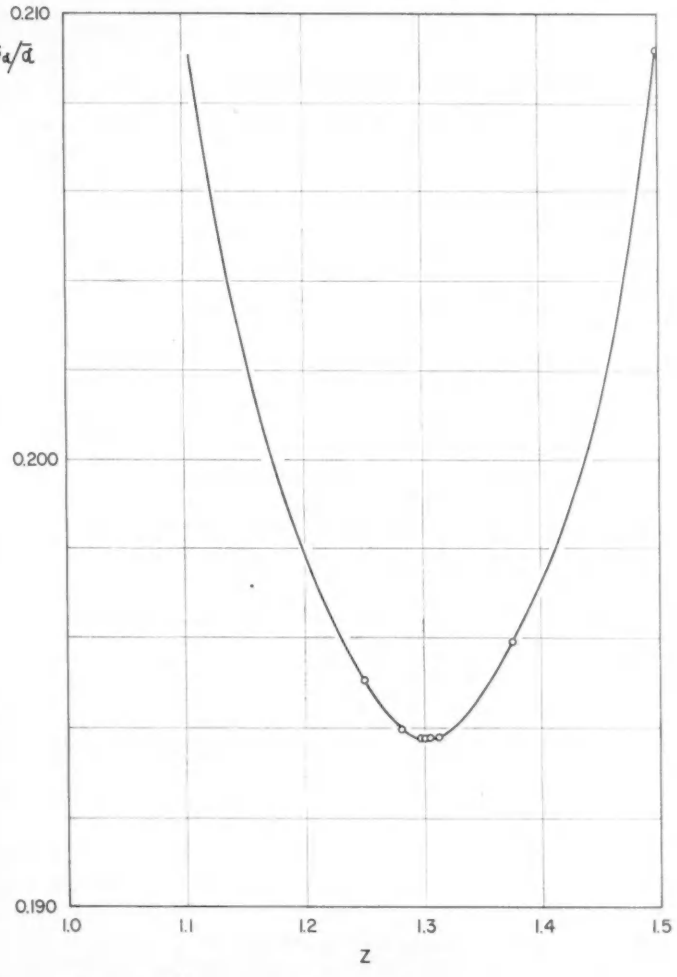

FIG. 3. Plot of relationship between relative standard deviation of α and trial value of z for 0/4 chinook data.

larger, and the resulting line of best fit will have a steeper slope than the average growth of the group warrants. This error may be visualized from a consideration of Fig. 4, 5, 8 and 10. For this reason z has been determined only from series

of lengths containing 3 or more successive values for each fish (2 or more complete growth years).

In the foregoing treatment, all of the variation in a sample has been ascribed to α: z was treated as an independent variable, determined without error, thus

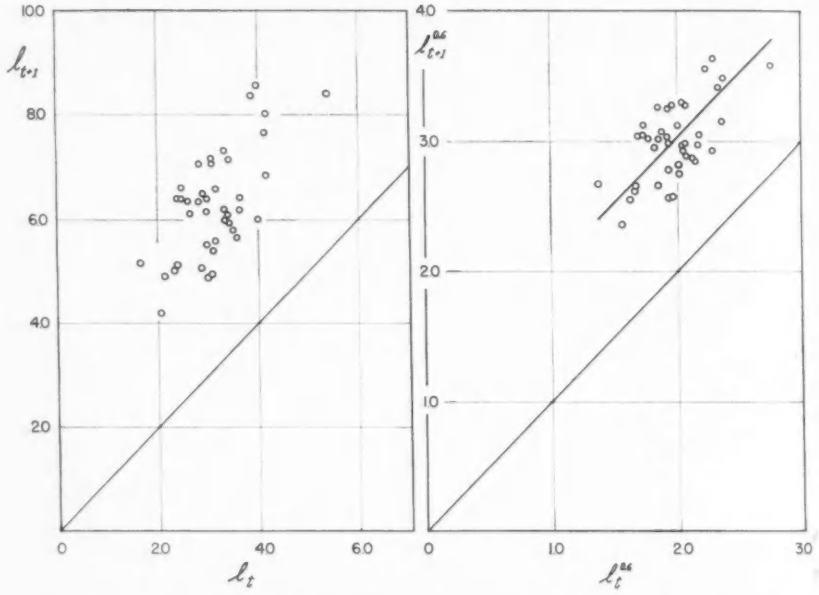

FIG. 4. Plot of l_{t+1} on l_t, and $l_{t+1}^{0.6}$ on $l_t^{0.6}$, 2/1 life history group of steelhead, in fresh water.

facilitating direct comparison of growth rates without regard to size or age, provided average growth in the compared groups is adequately described by the same z value. The variability of z values is further explored in the following section.

APPLICATION

Optimum z was determined for the freshwater phase of life history for the 3/1 steelhead group (Fig. 6). The 2/2 group was used to compute z for steelhead

TABLE IIA. Summary of statistics relative to optimum z as found by iteration.

Species	Life history type	Number of fish	z	"Mean" difference $\bar{\alpha}$	Variance s_x^2	Relative variance $s_\alpha^2/\bar{\alpha}^2$
Steelhead	3/1	47	0.59	0.69536	0.03749	0.07752
	2/2	52	1.00	11.14231	3.59302	0.02894
Chinook	0/3	150	1.32	31.64658	30.59787	0.03055
	0/4	60	1.30	27.57002	28.54040	0.03755
	0/5	8	1.11	12.56085	8.58274	0.05440

in salt water (Fig. 9). For chinook, z was independently computed for the 0/3, 0/4 and 0/5 groups (Fig. 11–13). Table II A summarizes the statistical results.

To gain some appreciation of the variability of z, two of the chinook groups were subdivided. For the 0/4 group (60 fish) the first and last 30 were treated separately. For the 0/3 group (150 fish) the first 30, second 31, third 43

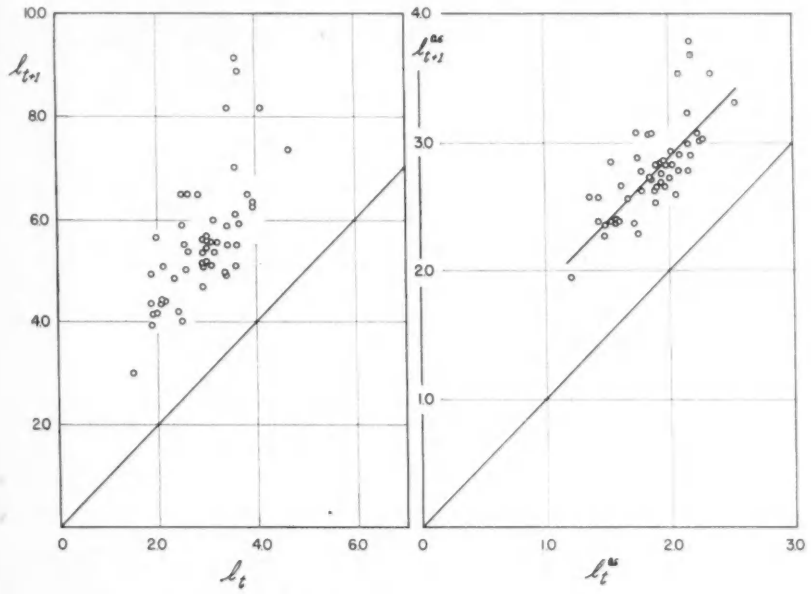

FIG. 5. Plot of l_{t+1} on l_t, and $l_{t+1}^{0.6}$ on $l_t^{0.6}$, 2/2 life history group of steelhead, in fresh water.

and remaining 46 fish were treated separately. The pertinent statistics are presented in Table II B: z is observed to vary between 1.25 to 1.46 when calculated from sub-groups of apparently random classification.

The parabolic relationship between values of z and the relative standard deviation of α is demonstrated in Fig. 3; the 0/4 chinook group was used in this

TABLE IIB. Values of z and accompanying statistics found for sub-groups of chinook.

Sub-group	Number of fish	z	$\bar{\alpha}$	s_α^2	$s_\alpha^2/\bar{\alpha}^2$
0/4	30	1.36	36.14174	33.35864	0.02550
	30	1.26	24.17668	27.27589	0.04666
0/3	43	1.42	43.60381	52.53047	0.02763
	46	1.25	24.26675	16.95653	0.02879
	30	1.30	31.19169	35.49098	0.03648
	31	1.46	53.29454	78.56134	0.02766

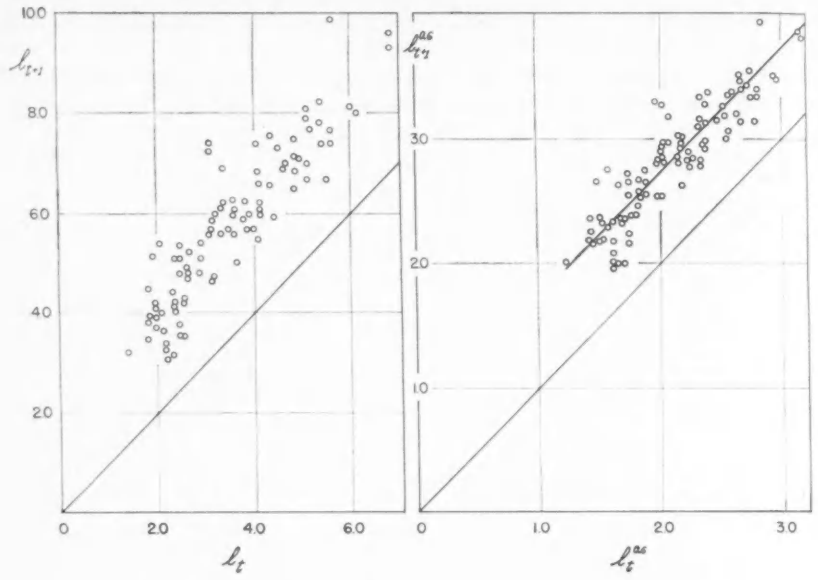

FIG. 6. Plot of l_{t+1} on l_t, and $l_{t+1}^{0.6}$ on $l_t^{0.6}$, 3/1 life history group of steelhead, in fresh water.

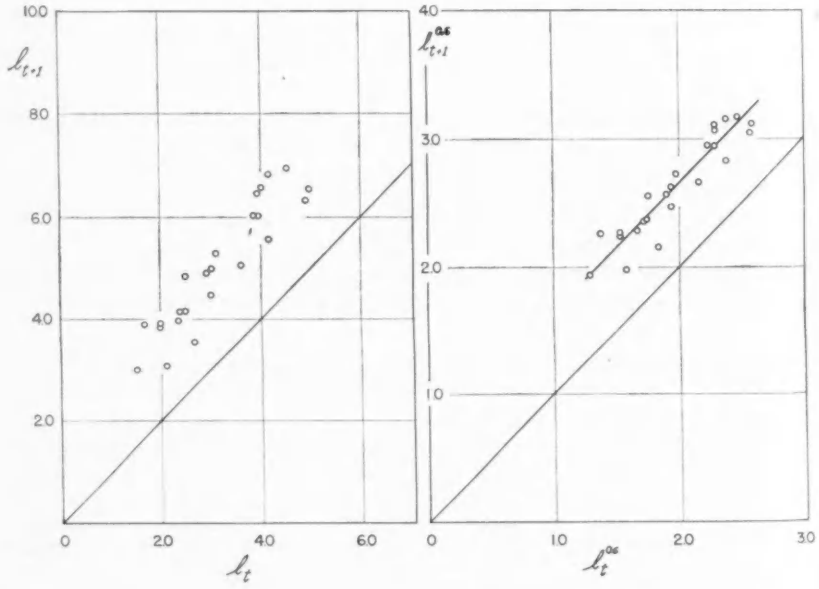

FIG. 7. Plot of l_{t+1} on l_t, and $l_{t+1}^{0.6}$ on $l_t^{0.6}$, 3/2 life history group of steelhead, in fresh water.

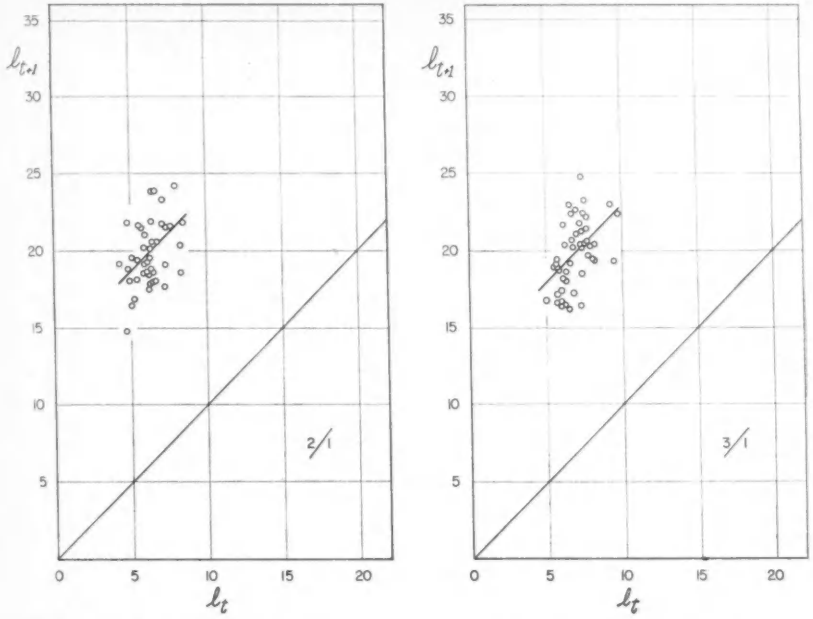

FIG. 8. Plot of l_{t+1} on l_t for 2/1 and 3/1 life history groups of steelhead in salt water.

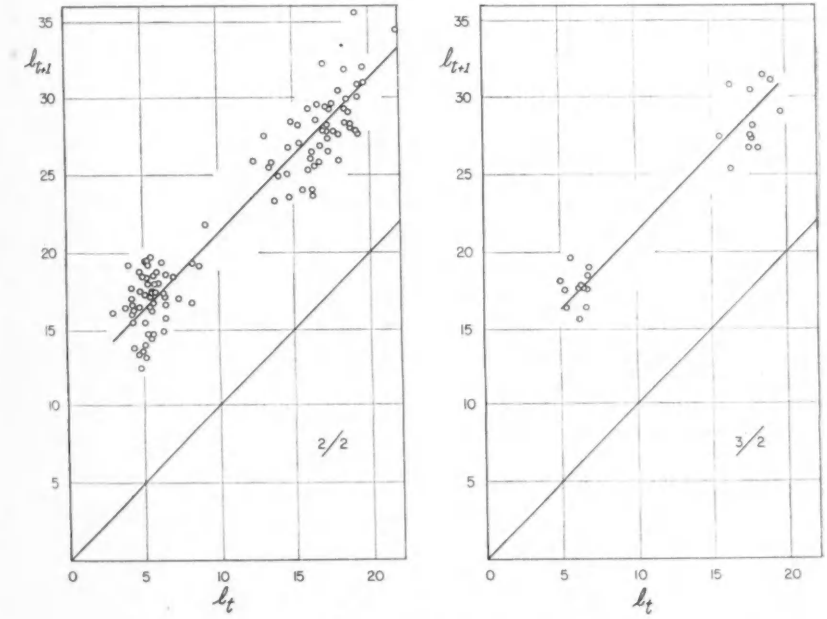

FIG. 9. Plot of l_{t+1} on l_t for 2/2 and 3/2 life history groups of steelhead in salt water.

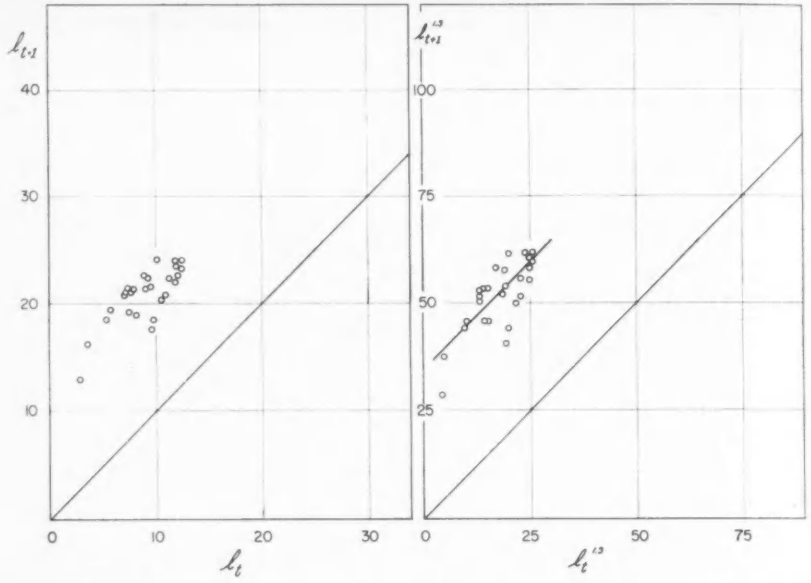

FIG. 10. Plot of l_{t+1} on l_t, and $l_{t+1}^{1\cdot3}$ on $l_t^{1\cdot3}$, for 0/2 life history group of chinook in salt water.

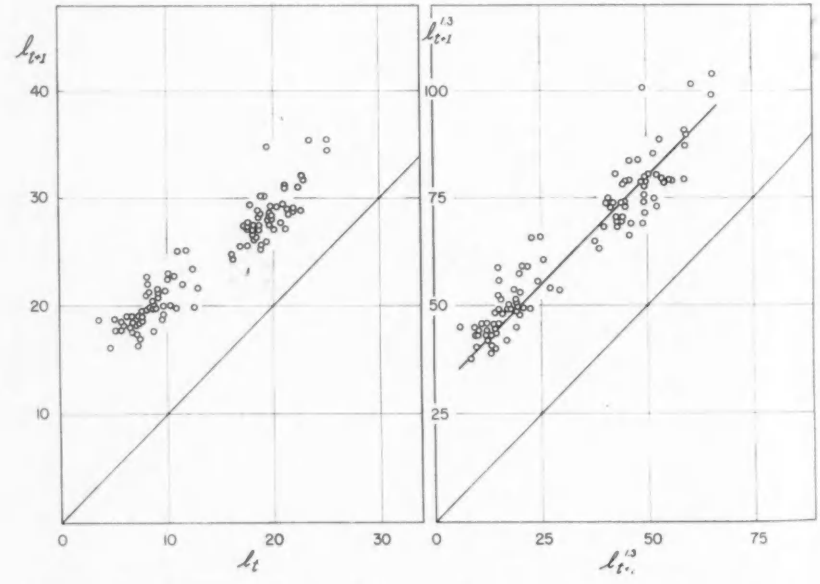

FIG. 11. Plot of l_{t+1} on l_t, and $l_{t+1}^{1\cdot3}$ on $l_t^{1\cdot3}$, for 0/3 life history group of chinook in salt water.

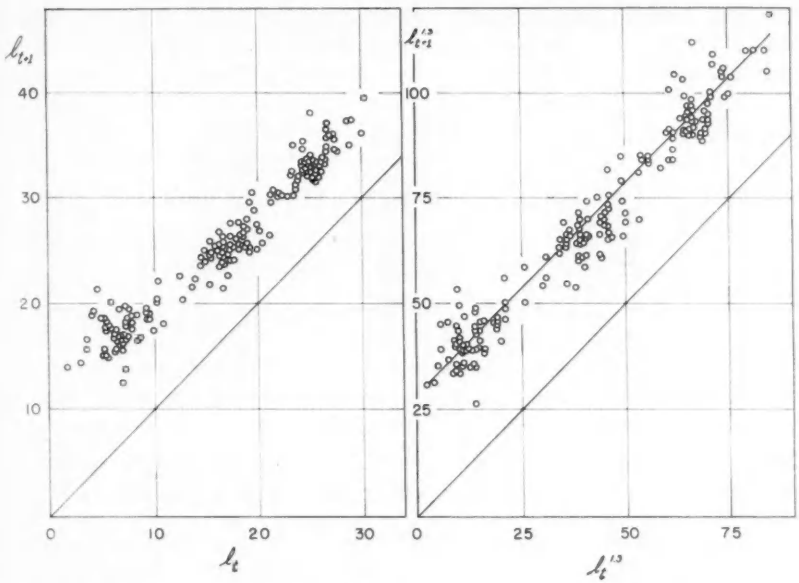

FIG. 12. Plot of l_{t+1} on l_t, and $l_{t+1}^{1.3}$ on $l_t^{1.3}$, for 0/4 life history group of chinook in salt water.

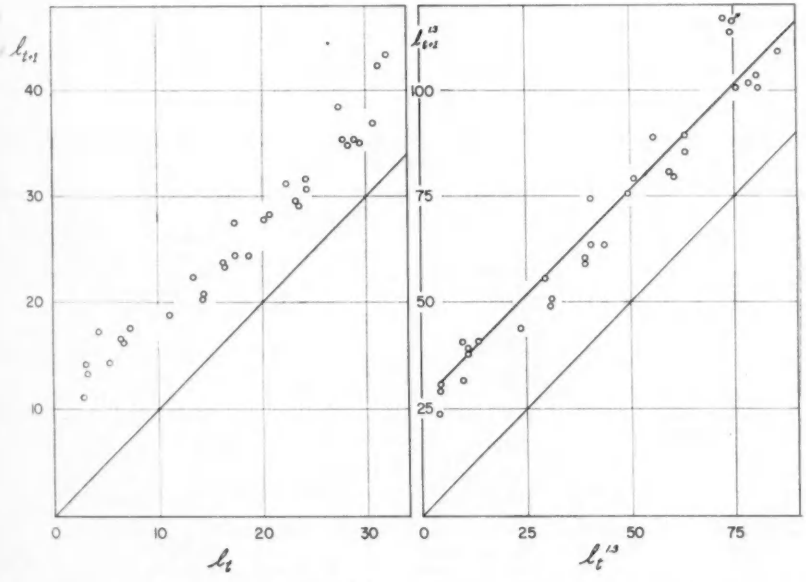

FIG. 13. Plot of l_{t+1} on l_t, and $l_{t+1}^{1.3}$ on $l_t^{1.3}$, for 0/5 life history group of chinook in salt water.

TABLE III. Statistics leading to solution (by ALWAC III E computer) of optimum z for the 0/4 group of chinook, $l^z_{t+1} = \alpha + l^z_t$.

z	$\bar{\alpha}$	s^2	$s^2_\alpha/\bar{\alpha}^2$	$s_\alpha/\bar{\alpha}$
1.00	8.75056	4.15228	0.05423	0.23287
0.50	1.04882	0.18507	0.16824	0.41017
1.50	57.65691	145.35886	0.04373	0.20912
1.25	22.79004	19.75700	0.03804	0.19504
1.375	36.34871	50.71640	0.03839	0.19593
1.3125	28.80405	31.16188	0.03756	0.19380
1.28125	25.62648	24.71367	0.03763	0.19398
1.29688	27.17020	27.72342	0.03755	0.19378
1.30469	27.97554	29.38511	0.03755	0.19378
1.30078	27.50020	28.54040	0.03755	0.19378

example (Table III). Optimum z lies close to 1.3. A parabolic solution gave $z = 1.33$. From Fig. 3, a change of 0.05 in either direction from optimum z is seen to effect a change of only approximately 0.001 in relative standard deviation. Thus the attachment of significance beyond the first decimal place in z is unwarranted.

Comparisons of growth rates for different life history groups are only valid when the same value of z is used for the groups compared. Accordingly, for growth comparisons the data (Table I) were treated as follows:

Steelhead, freshwater, $l^{0.6}_{t+1} = \alpha + l^{0.6}_t$

Steelhead, marine, $l_{t+1} = \alpha + l_t$

Chinook, marine, $l^{1.3}_{t+1} = \alpha + l^{1.3}_t$

TABLE IV. Analysis of variance on steelhead and chinook for growth differences between life history groups and sexes.

Environment	Grouping	Degrees of freedom	"F" ratio	Probability
Freshwater steelhead	Life history	3	35.8	$< .005$
	Sexes	1	0.4	$> .25$
	Interaction	3	1.4	$> .25$
	Error	203		
Salt water steelhead	Life history	3	17.4	$< .005$
	Sexes	1	9.7	$< .005$
	Interaction	3	0.7	$> .25$
	Error	208		
Salt water chinook	Life history	3	13.0	$< .005$
	Error	538		

Values of l_1^z, l_2^z, l_3^z, etc., and α_{12}, α_{23}, etc., were computed for each individual. These transformations are presented graphically for each major grouping of fish in Fig. 4–13. All length measurements are of fork length in inches. Differences between α values for life history groups and sexes were tested by analysis of variance, with appropriate correction for disproportionality in sample size (Snedecor, 1946). Results are presented in Tables IV and V.

From these results the following conclusions for steelhead may be drawn:

1. In fresh water, male and female steelhead grow at approximately the same rate. In salt water males grow significantly faster than females.
2. Growth rate is inversely related to eventual life history events in both fresh and salt water. Slow-growing steelhead failed to become smolts at completion of the second growth year and remained an additional year in fresh water. Fast-growing individuals migrated at the completion of the second growth year.
3. In salt water, the two freshwater growth groups further subdivided into fast- and slow-growing fractions. The faster growing fraction of the former slow-growing group matured following the first ocean growth year. The slow-growing fraction matured after two ocean growth years. The same subdivision took place in the freshwater fast-growing group. These results are in part

TABLE V. Average growth (measured by α) for groupings of steelhead and chinook showing significant differences.

Environment	Life history type	Mean α	
		(*both sexes*)	
Steelhead Freshwater $z = 0.6$	2/1	1.02	
	2/2	0.90	
	3/1	0.73	
	3/2	0.65	
Steelhead Salt water $z = 1.0$		♂	♀
	2/1	13.63	13.34
	2/2	11.73	10.75
	3/1	13.05	12.54
	3/2	12.20	10.68
		(*both sexes*)	
Chinook Salt water $z = 1.3$	0/2	34.10	
	0/3	29.82	
	0/4	27.49	
	0/5	25.89	

substantiated by observations of Alm (1949) and by Elson (1957) for *Salmo salar*, and of Parry (1958) for *S. salar*, *S. trutta*, and *S. gairdneri*.

For chinook salmon, both sexes were lumped. As in the steelhead in salt water, the fastest growing fish matured at the earliest age.

DISCUSSION

Growth of steelhead and chinook has been described using the basic premise that growth rate (dw/dt) increases proportionally to increase in weight raised to a fractional power (w^x). No experimental evidence has been offered to justify the use of this relationship, however empirical growth data for those species considered were approximately linear after transformation by a suitable choice of the length exponent z. In this manner these data are adequately described by the hypothesis. Equation (3) has analogy with empirical expressions of other physiological rates, summarized as equation (3a). Adolph (1949) listed 33 physiological rates (O_2 uptake, N_2 excretion, ventilation, etc.) that appear (for mammals) adequately described by the general parabolic equation (3a), i.e. that the rates are proportional to w^x. Zeuthen (1953) and Weymouth *et al.* (1942) extend these observations to respiration of various individual organs. This parallelism underlines the coordinated aspect of a living system (Haldane, 1936). Various physiological rates are not independent but correlated. That growth rate is also part of the correlated system appears to be a tenable hypothesis. Kleiber (1947) suggested from a review of literature that food capacity, food intake and gain in weight in farm animals should all be related to the ¾ power of weight. Barrett (Fry, 1957) demonstrated for rainbow trout (5–75 grams) in freshwater and under standard conditions that the rate of O_2 consumption increases in proportion to $w^{x=0.8}$. It was shown in a previous section that juvenile steelhead in freshwater grew proportionally to $l^{z=0.6}$. Assuming that weight is proportional to l^3, then growth rate in terms of weight[9] was proportional to $w^{x=0.8}$. This similarity of exponents suggests the possibility that values of x or z for growth equations may be derived from a comparative study of standard metabolic rate over a range of sizes. Data are not at present available to make such a comparison.

The phenomenon of "stanzas" is characteristic both of metabolic rates and growth rates. Anadromous salmon and trout experience at least two rather abrupt physiological transformations (Hoar, 1939, 1957; Hoar and Bell, 1957; Green, 1926), one at parr–smolt transformaton, the other at maturity. While published data have not been found describing the relation of standard metabolic rate to weight for fish in each stage of life history, certain analogies may be drawn from other groups of animals. For mammals, Brody (1945) has described discontinuities or "breaks" in weight–specific metabolic rate curves, and he directed attention to similar breaks in growth curves. He has suggested a direct connexion between metabolic rate and growth rate. Zeuthen (1953, 1955) extended these observations to include several poikilotherms. Martin (1949) has demonstrated

[9] $x = 1 - \frac{z}{y} = 1 - \frac{0.6}{3} = 0.8.$

sharp breaks in relative growth lines for several species of fish and related these discontinuities to ossification and maturity. Hiatt (1947) demonstrated a sharp break in relative growth of gut length of *Chanos chanos* occurring at approximately 100 mm body length. The present data suggest that increase in growth rate is proportional to increase in standard metabolic rate as measured by O_2 consumption. This analogy further suggests that the exponent x may be primarily established for each growth stanza by the endocrine control system, and that any changes in environmental opportunity will influence the proportion constant k. The analogy has the limitation that growth stanzas may be delimited by ecological as well as physiological thresholds. Thus within any physiological growth stanza (within which x may be constant) there may be more than one ecological growth stanza, each characterized by a particular k, or perhaps progressive shift of k from a low to a high value or *vice versa.*

A growth equation currently popular in fisheries science is that of von Bertalanffy (1938, 1949, 1957). It is equivalent to the "self-inhibiting" growth equation of Brody (1945) which is much used on mammals, to the modified exponential of Croxton and Cowdan (1946), and to the graphic transformation presented by Walford (1946). Von Bertalanffy considers growth to be the net result of an open system of supply and demand of resources which can be metabolized. Since material must enter the organism through a surface, and maintenance demand is proportional to mass, given isometric growth the organism will eventually reach a size where supply and maintenance demand are in equilibrium. Von Bertalanffy's basic equation is therefore:

$$dw/dt = HS - kw \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

where S denotes surface of some limiting membrane,

w denotes mass, and

H and k are proportion constants.

With isometric growth and constant density a surface is proportional to the square of the length while mass is proportional to length cubed. Introducing equation (6) for mass, and letting

$$S = pl^2$$

equation (13) takes the form:

$$dl/dt = \alpha - \beta l \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

where $\alpha = \dfrac{Hp}{3q}$ and $\beta = \dfrac{k}{3}$.

Integrated, equation (14) depicts growth as a process in which first differences of a length series l_1, l_2, l_3, etc. decrease by a constant percentage, i.e. on an arithmetic plot of l_{t+1} against l_t, points fall on a straight line which intercepts a 45° diagonal with origin 0,0 (Walford, 1946). Von Bertalanffy's equation has found practical application in yield equations by Beverton and Holt (1957).

There are several assumptions inherent in von Bertalanffy's growth equation that need to be examined. Firstly, emphasis is placed on the "two-thirds" rule or surface rule (see Brody, 1945) which states that standard metabolism, as measured

by rate of O_2 consumption, increases as the $\frac{2}{3}$ power of weight. Brody (1945), Adolph (1949), Prosser (1950), Zeuthen (1953), von Bertalanffy (1957), and others have indicated that, more accurately, metabolic rate increases approximately as the 0.73 power of weight. Kleiber (1947) has summarized many of the inadequacies of the surface rule and cautions against the assumption of any strict proportionality between "true" body surface and metabolic rate.

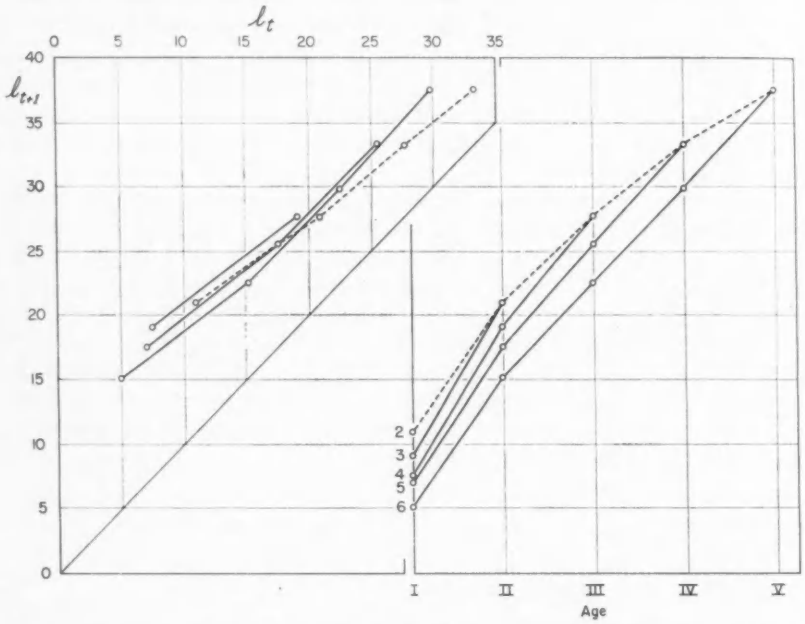

FIG. 14. Two treatments of data by "Walford transformation" leading to different conclusions. Chinook, salt water. See text for explanation.

Secondly, as pointed out by Cohn and Murray (1927), there is no reason for growth of internal surfaces to be isometric. Szarski *et al.* (1956) have found the absorptive area of the gut of *Abramis brama* to grow by means of infolding approximately in proportion to the weight. Klust (1939, 1940) and Al Hussaini (1949) have demonstrated ontogenetic increase in relative gut length and/or relative absorptive surface in cyprinids. Hiatt (1947) demonstrated a relationship between allometric growth of the gut of *Chanos chanos* and a size specific change in dietary habit. Price (1931) demonstrated positive allometry in growth of gill surfaces ($G = 8.65\ w^{0.785}$) of *Micropterus dolomieu*. It would appear to be the unusual case where a surface membrane restricts growth in the manner of equation (13).

The apparent fit of a von Bertalanffy equation or Walford line to growth data may in some cases be forced, as a result of the method of sampling or combining the data. Average lengths at the completion of an annulus for the several groups of chinook are used as an example (TableVI). In Fig. 14 these

TABLE VI. Average size-at-age for life history groups of chinook salmon, as estimated by direct proportion back calculation.

Life history type	Number of fish	Size at end of anulus (fork length in inches)				
		1	2	3	4	5
0/1*	4	10.9				
0/2	27	9.0	20.8			
0/3	150	7.5	19.1	27.7		
0/4	60	7.0	17.4	25.5	33.3	
0/5	8	5.0	15.1	22.5	29.9	37.6

*Sample of four fish captured in their second year of life, not included in Table 1 or previously considered.

data are graphically transposed from an average-size-at-age plot (right side) to a l_{t+1} on l_t plot (left side). Two treatments have been used. The first, represented by solid lines in both sides of the Figure, considers the life history groups separately. The dashed line in both sides of the Figure represents the case where only fish captured in their fourth growth year are used to compute average size at age III, etc. This latter method reflects "Lee's phenomenon" (Lee, 1920) which can be accounted for by the growth rate–life history relationship previously demonstrated (Table IV), by selectivity of the fishing gear for larger fish, and by shoaling of chinook according to stage of maturity (Neave, 1951; Parker and Kirkness, 1956) or by a direct correlation between growth rate and mortality rate (Gerking, 1957). These two methods of treatment lead to diverse conclusions. By considering each life history group separately growth is seen to approach parallelism with the 45° diagonal. The second treatment depicts growth rate as gradually decreasing and forms an approximately linear plot (Walford line) which will intercept the 45° diagonal. Thus the latter treatment depicts growth as a von Bertalanffy equation. In the present case the latter method leads to a serious underestimation when predicting future increment to the stock from growth.

Thus far, growth of the average individual of sub-groups of the population has been presented. For chinook, the von Bertalanffy equation is shown to oversimplify and underestimate the growth of a hypothetical "average" fish in the entire population. Each component group should be weighted according to its actual abundance in the population, a proposition necessitating a schedule of mortality rates which are related to growth rates.

Considering that approximately only 5% of steelhead (Maher and Larkin, 1956) and substantially no chinook (for possible exceptions see Robertson, 1957) survive for a second spawning, and considering selectivity of fishing gear for larger fish, the relative magnitudes of growth rate and total mortality rate in these populations are undoubtedly directly correlated (see Gerking, 1957, for comment on other species). This aspect of population dynamics has been little explored and presents a necessary field for study before the average growth of a population can be depicted from a consideration of growth of individuals.

SUMMARY AND CONCLUSION

Growth in fishes has here been visualized as a series of stanzas within each of which the growth rate is proportional to a constant multiplied by a fractional power of weight, i.e.:

$$dw/dt = kw^x$$

This approach implies that in each growth stanza the increment of weight can be related to the weight in the same way as various physiological rates are related to weight. In both of these instances a complex of processes may be involved which are best summarized mathematically in the relatively simple parabolic equation. However, the interpretation attached to the constants k and x is complicated in the case of growth rate because both ecological and physiological factors act as determinants.

The similarity in x, the exponent of weight for metabolic rate and growth rate suggests that x measures the complex of physiological processes while k measures ecological opportunities. Whether or not this is true does not alter the usefulness of the equation in describing growth processes. This equation can be considered as an example of General Systems Theory approach of von Bertalanffy (1950, 1951). In addition, growth stanzas may be delimited both by ecological and by physiological thresholds. Finally, growth of the individual or of a group of individuals may be characterized by different values of the constants k and x, necessitating separation of a population into "life history" groups, etc. These groups may be characterized by mortality rates associated with their respective growth rates.

The prediction of growth increment in a population thus requires:

1. Separation into life history groups (and possibly sex), each characterized by particular growth rates.
2. Determination for each group and for each growth stanza of appropriate value of the constant k for an average exponent x.
3. Determination for each group and each growth stanza of appropriate total mortality rate.
4. Summation of the increments to each group with correction for mortality.

Sampling data of a population obtained through a selective fishery cannot be used *per se* to depict "average individual", and detailed mortality studies, as related to size and growth rate are needed. A relationship between growth rate and metabolic rate is suggested as a means of independently establishing one basic parameter of the growth equation. These two approaches constitute profitable fields of research for agencies engaged in fisheries management.

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The Effect of Sodium Chloride on Proteolysis and on the Fate of Amino Acids Present in the Muscle of Codfish (*Gadus callarias*)[1]

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ABSTRACT

The rate of proteolysis and the deamination of free amino acids in cod muscle treated with 4, 8, 12 and 16% sodium chloride varies with the sodium chloride content and temperature. Proteolysis of the fish muscle protein is completely inhibited at concentrations of 16 and 12% sodium chloride. Trimethylamine formation is inhibited by 16% sodium chloride for at least 15 days. Both inhibitions take place at either 15 or 25°C. In salted muscle deamination can occur in the absence of trimethylamine formation. The reaction appears to be hardly influenced by salt. Indole formation is completely inhibited by 8% salt at either 15 or 25°C.

INTRODUCTION

Fish spoilage particularly in its more advanced stages is largely associated with protein breakdown. Beatty and Collins (1939), investigating the changes that occur in proteins and amino acids of cod muscle press juice, showed that deamination of free amino acids occurred only after a pronounced formation of trimethylamine and that the free amino acid content increased only after rather advanced spoilage. A similar observation was made by Dyer and Mounsey (1945) with respect to non-volatile amines. These are assumed to originate from the decarboxylation of amino acids after pronounced decomposition of cod muscle. Labrie and Gibbons (1937) investigated the effects of temperature and salt concentration on the spoilage of cod muscle press juice. They noted that sodium chloride retards the formation of trimethylamine and that the rise in volatile bases, which occurs before the appearance of trimethylamine, is due to the production of ammonia. A bacteriological study by Castell and Snow (1951) deals also with the inhibition of the formation of trimethylamine by salt. Winter (1950) has shown that the production of ammonia, trimethylamine, and amino acids is appreciably faster in unsalted than in salted fish muscle. Soudan (1955) studied the relation between the extent of protein breakdown and the browning of salted cod muscle.

The purpose of the present investigation is to contribute further to a solution of the problem of the prevention of spoilage of codfish muscle by salt. The kinetics of protein degradation, the fate of the amino acids involved and formation of trimethylamine and of indole have been studied at different sodium chloride levels, at 15 and 25°C.

EXPERIMENTAL

Investigations on whole salted cod muscle present certain experimental difficulties. Studies on press juice would show only the behaviour of soluble protein.

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Consequently minced muscle has been used in these experiments, in which a homogeneous distribution of salt and the initial bacterial flora was obtained by grinding and mechanical mixing.

Materials

The fish used were caught in July and delivered to the laboratory in less than one day. They were immediately filleted and each fillet was run through a meat chopper. A total of 14 fillets of roughly 500 g each, representing 7 fish, was used as the starting material.

Methods of Analysis

Total nitrogen was determined by the Kjeldahl method as described by Hawk *et al.* (1947).

Free amino acids were determined at pH 2.5 by the ninhydrin titrimetric method of van Slyke *et al.* (1941). The reaction requires the presence of the carboxyl and of the α-amino groups in the free unconjugated state. Peptides do not interfere.

Total volatile bases and trimethylamine (TMA) were estimated by Beatty and Gibbons' (1937) modification of the micro diffusion technique of Conway and Byrne (1933).

Ammonia was calculated from the difference between total volatile nitrogen and TMA nitrogen.

Indole was determined by the *p*-dimethylamino-benzaldehyde method as described by Duncan *et al.* (1957).

Deamination of the α-amino acids was followed by determining the disappearance of free amino acids and the formation of ammonia, according to Beatty and Collins (1939).

Hydrolysis of muscle protein into fragments of lower molecular weights, soluble in ethanol (80%), was measured by the decrease in nitrogen in the residue after alcoholic extraction.

Preparation of Samples

The difficulty of accurate sampling during the experiment was overcome by incubating samples of identical weights in separate flasks and by using the total contents of each flask for each investigation.

Salt concentration and temperatures were chosen in the ranges frequently encountered during the industrial preparation of salt cod (Fougère, 1952; Beatty and Fougère, 1957; van Klaveren and Legendre, 1959). In this type of investigation the period during which observations are made is usually chosen arbitrarily. In an earlier series of experiments changes were followed for 7 days. The time was later extended to 14–15 days. Very similar results were obtained in repeated experiments. In order to increase the validity of the comparative tests, one and the same lot of minced muscle was used for all experiments reported in this paper.

Experimental Procedures

To four fractions of the ground starting material NaCl was added to obtain final concentrations of 4, 8, 12 and 16% respectively (wet basis). A homogeneous distribution of the NaCl in the minced muscle was obtained by means of a Hobart mixer, model 150.

Each fraction was divided into two series of samples, one of which was stored at 15°C the other at 25°C. Each sample of known nitrogen content had a weight of exactly 50 g and was kept in a 500-ml tightly corked Erlenmeyer flask.

At suitable time intervals of 24 or 48 hours, a calculated amount of NaCl was added to one sample of each series to give it a final concentration of 16%. This was done in order to have uniform conditions throughout the tests.

The next step consisted in extracting the fish muscle with ethanol, which not only extracts non-protein nitrogen (Shewan *et al.*, 1952), but also arrests enzymic activity by precipitation of the proteins present. Repeated experiments demonstrated that the recovery of free α-amino acids was 95% or better. The determination of volatile bases was discontinued when the pH of the material increased to values above 7. Ethanol (95%) was added in sufficient quantity to obtain a final concentration of 80% (v/v) with the water already contained in the sample. The sample was then homogenized for about 1½ minutes in a Waring Blendor fitted with a screw cap. The alcoholic suspension was heated to 40°C for 90 minutes, then filtered hot. The residues were washed twice with 80% ethanol at 40°C, air dried, and stored dry for subsequent determinations of protein nitrogen. For each sample the alcoholic extracts, combined with the wash liquids, amounted to 350 ml of a solution in which the ethanol concentration was 80% (v/v). This solution was evaporated to near dryness in an air current, and then dissolved in water to a volume of 50 ml and stored at –15°C for subsequent determination of free amino acids, TMA and indole.

RESULTS AND DISCUSSION

The results are shown in Fig. 1, 2, 3, 4 and also in Table I. The inhibitory effect of salt appeared to be quite different in the various reactions which have been studied.

The hydrolysis of muscle proteins was completely inhibited at the higher salt concentrations of 16 and 12% at both temperatures (Fig. 3 and 4) and with 8% NaCl at 15°C. However with 8% NaCl at 25°C the proteolytic effect under study started already after one week. With 4% NaCl pronounced hydrolysis of muscle proteins took place at 25° as well at 15°C. A comparison of the values obtained with 0% and 4% NaCl shows that the latter concentration is inadequate as its inhibitory effect on the hydrolytic breakdown of muscle proteins was very limited (Fig. 1).

In the absence of hydrolysis of proteins an initial limited increase in amino acids content was noted over a wide range of salt concentrations (Fig. 2, 3, 4). This formation of free amino acids is interpreted as the result of hydrolysis of peptides originally present in the muscle. Our observation is in agreement with

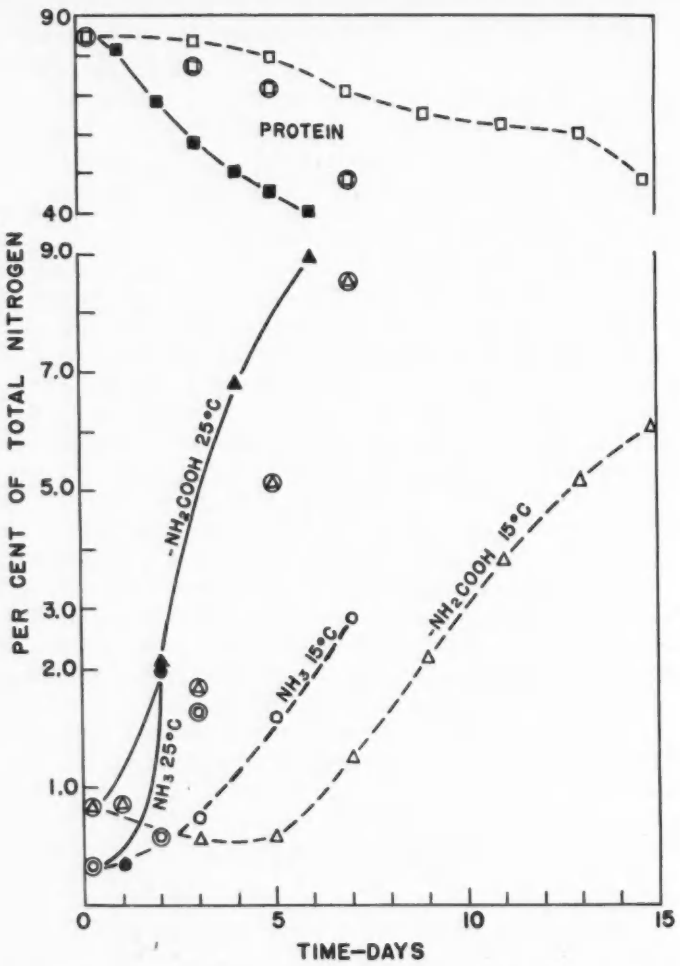

FIG. 1. Changes in α-amino acids, ammonia and protein in minced cod muscle with 4% NaCl at 15° and 25°C, and in minced unsalted cod muscle at 15°C.

α-Amino acids (α-amino nitrogen)	△ at 15°C. ▲ at 25°C. ⊘ at 15°C (unsalted muscle).
Ammonia nitrogen	○ at 15°C. ● at 25°C. ◎ at 15°C (unsalted muscle).
Protein (nitrogen in residue of 80% ethanol extraction)	□ at 15°C. ■ at 25°C. ⊡ at 15°C (unsalted muscle).

statements by other workers according to whom peptides do occur in the muscle of live fish, and are broken down *post mortem* (Jones, 1956; Siebert, 1958).

Salt appeared to have only a slight retarding effect on the deamination of α-amino acids, which however was more pronounced at higher concentrations. A display of deamination is especially evident in experimental conditions where no perceptible hydrolysis of muscle proteins occurred. With 16% NaCl at 25°C deamination is indicated by a simultaneous increase in ammonia and disappearance

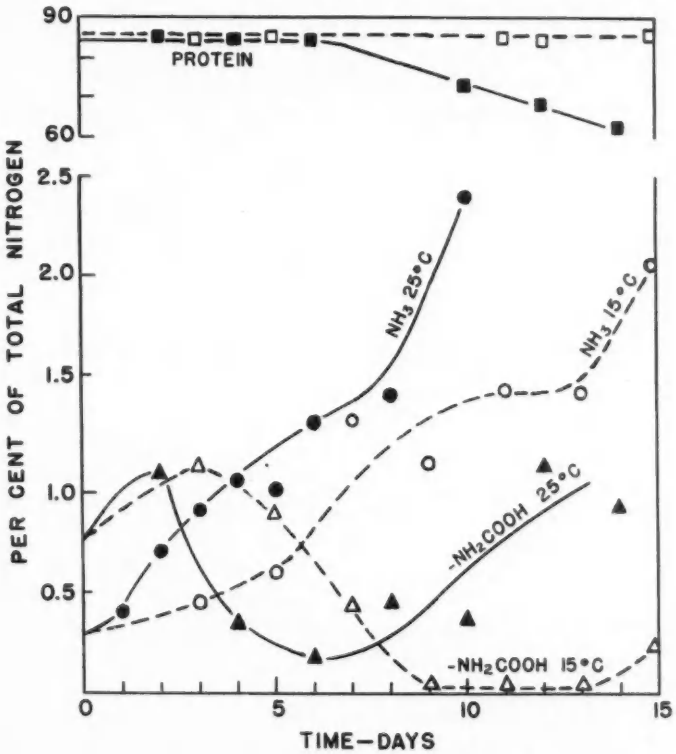

FIG. 2. Changes in α-amino acids, ammonia and protein minced cod muscle with 8% NaCl at 15° and 25°C. (For legend, see Fig. 1.)

of free amino acids. Similar changes occurred with 12% NaCl and the process was more rapid at 25° than at 15°C. With 8% NaCl at 15° the breakdown of amino acids is completed still earlier. An inhibition of this process took place only at the highest salt concentration (16%) and the lower temperature (15°C) used in the experiment (Fig. 4).

During the hydrolysis of muscle proteins the effect of the deaminase tends to be exceeded by the liberation of free amino acids. At 25°C with 8% NaCl the

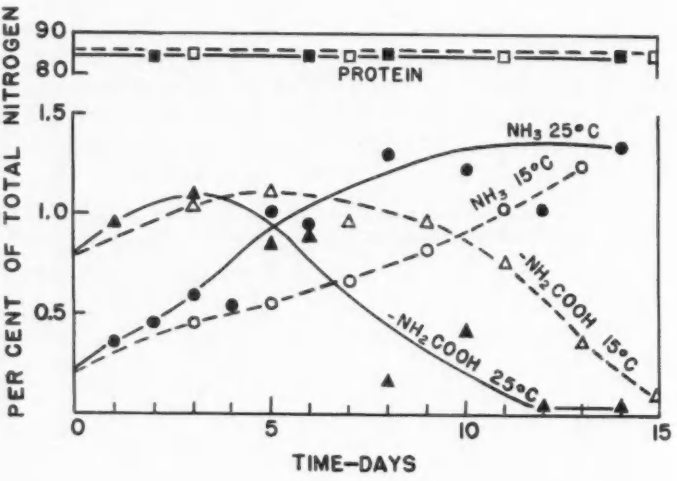

FIG. 3. Changes in α-amino acids, ammonia and protein in minced cod muscle with 12% NaCl at 15° and 25°C. (For legend, see Fig. 1.)

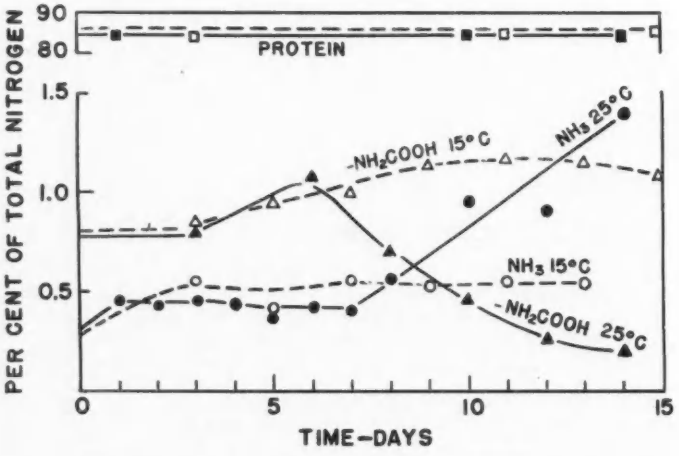

FIG. 4. Changes in α-amino acids, ammonia and protein in minced cod muscle with 16% NaCl at 15° and 25°C. (For legend, see Fig. 1.)

free amino acids show a decrease during the first 6 days. But thereafter, when the protein is broken down, the tendency is reversed. With 4% NaCl proteolysis is so pronounced that its ultimate products, namely the amino acids, show a sharp increase during the course of the experiment. At this stage ammonia is formed in large amounts, presumably due to a partial destruction of the liberated amino acids by deamination.

In the experiments of Beatty and Collins (1939), employing fresh fish, deamination started only when the trimethylamine had reached a high level. However, the present investigation shows that in the presence of salt, deamination can also occur at a very low TMA level. The TMA values are shown in Table I.

TABLE I. Formation of trimethylamine.

Description of the samples	Duration of storage	Trimethylamine nitrogen per 100 g of unsalted muscle
	days	*mg*
4% NaCl, 15°C	3	40.5
" "	5	76.7
4% NaCl, 25°C	1	7.0
" "	2	55.3
8% NaCl, 15°C	1 – 9	<1.0
" "	11	7.5
" "	13	12.4
8% NaCl, 25°C	1 – 3	<1.0
" "	4	6.3
" "	6	8.1
" "	8	20.4
" "	10	25.6
12% NaCl, 15°C	3 – 15	<1.0
12% NaCl, 25°C	1 – 4	<1.0
" "	6	1.7
" "	8	1.7
" "	10	11.5
" "	12	25.1
16% NaCl, 15°C	3 – 15	<1.0
16% NaCl, 25°C	1 – 14	<1.0

Indole was found to be absent at salt concentrations of 8% or more. However, 0.40 mg indole per 100 g of muscle was found on the seventh day in the sample treated with 4% salt and incubated at 15°C, and 0.25 mg per 100 g of muscle was found on the second day in a similar sample incubated at 25°C. The formation of indole is therefore inhibited at the medium and high salt concentrations, which are in the range of those used by salt fish industry. The presence or absence of this decomposition product of trytophan was determined as a confirmatory test for the offensive stage of fish spoilage as indicated by Reay and Shewan (1949).

The question which of the reactions described above are caused by fish muscle enzymes and which by micro-organisms will be the subject of another study.

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Notes

Distribution of a Lipase Enzyme in Lingcod Fillets and the Effect of Low Temperature Storage on its Activity

It is known that fish fillets deteriorate gradually even when stored in the frozen state at temperatures as low as –20°C. One type of reaction which occurs in fillets at these temperatures is the formation of free fatty acids. Dyer and his co-workers (1956a, 1956b, 1959) have made extensive studies on the formation of the free fatty acids in various species of fish and at different storage temperatures. Although this formation of free fatty acids has been known for several years, as yet no definite mechanism of the acid-forming reactions has been established. The fatty acids could arise from hydrolysis of triglycerides or from the breakdown of phospholipids. These reactions could be brought about by enzymes in the fish flesh, or by bacterial action, or even by non-enzymic catalysis within the fish muscle.

Investigations were therefore carried out on lingcod muscle to determine whether there were any enzymes in the flesh capable of hydrolysing fats. These studies showed that an enzyme capable of splitting off fatty acids from triglycerides was indeed present in lingcod muscle (Wood, 1959). This note deals with further work on the distribution of this lipase in lingcod fillets, and on the effect of storage on the activity of the enzyme.

Fresh lingcod were filleted and skinned, and each fillet was cut into sections which were numbered consecutively beginning at the tail end of the fish. The fillet sections were glazed, wrapped individually in polyethylene bags and stored at -20°C.

The lipase activity was isolated from the fillet sections as follows. The frozen flesh was chopped into small pieces and homogenized in 3 volumes of ice-cold distilled water for 45 seconds. The homogenate was centrifuged at 20,000 *g* for 20 minutes and the supernatant liquid decanted. The latter was filtered through glass wool and used immediately for the measurement of lipase activity by the manometric determination of carbon dioxide evolved from a bicarbonate buffer as a result of the liberation of fatty acids by the enzyme. The experimental conditions employed were the same as those described previously (Wood, 1959).

Protein estimations were performed using the method of Kingsley (1939) as modified by Snow (1950).

The lipase activity of the preparations from the different sections of fillet are shown in Fig. 1. The activity increased progressively from the tail section to the head section. The amount of protein extracted from the flesh showed this same trend (Fig. 1) but the percentage increase in the protein nitrogen was much less than the percentage increase in the enzyme activity.

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Since the lipase is not uniformly distributed throughout the flesh, care must be taken during comparative studies in obtaining a sample which is representative of the fillet as a whole. This difficulty was circumvented in the "storage experiment", described below, by taking the average of three values obtained from tail, middle and head sections of the fillet respectively, as the value for the whole fillet.

The lipase activity in lingcod fillets after storage of the flesh at –20°C for various lengths of time is shown in Fig. 2. Storage at this temperature did not cause any great change in the lipase activity, but a gradual and rather ill-defined decrease

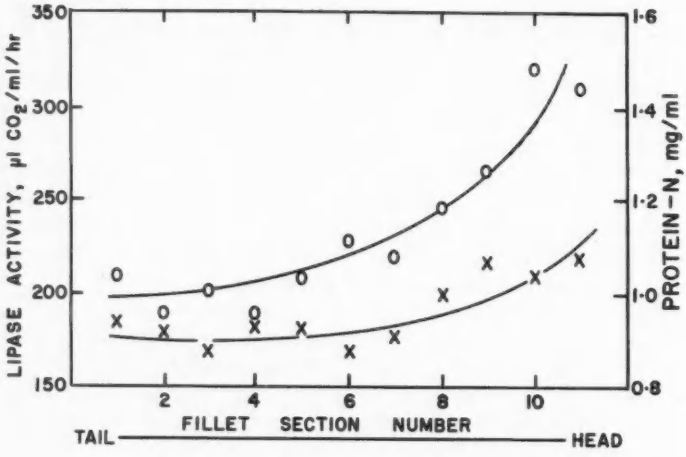

FIG. 1. The distribution of a lipase enzyme in lingcod fillets (o—o) and the amount of soluble protein in various sections of the fillet (x—x). All values are given per millilitre of enzyme preparation.

was observed. However, the enzyme was still very active after 12 weeks of storage at –20°C.

The formation of free fatty acids at –20°C is a slow process and continues for many weeks. This confirms that the enzyme responsible for the process must be stable under these conditions of storage.

Figure 2 also shows the effect of storage of the fillets on the amount of extractable protein. The changes in the extractable protein content were small and closely paralleled the changes in the lipase activity: the activity per unit weight of protein (specific activity) remained constant from sample to sample. This differs from the results obtained for the lipase distribution in the fillet where the specific activity increased from tail section to head section.

The investigations reported here give further evidence that the lipase enzyme found in lingcod muscle, if it is to be responsible for the formation of free fatty acids in frozen fillets, has the necessary properties. However, the evidence is by no means conclusive. The fact that phospholipids constitute a major portion of the

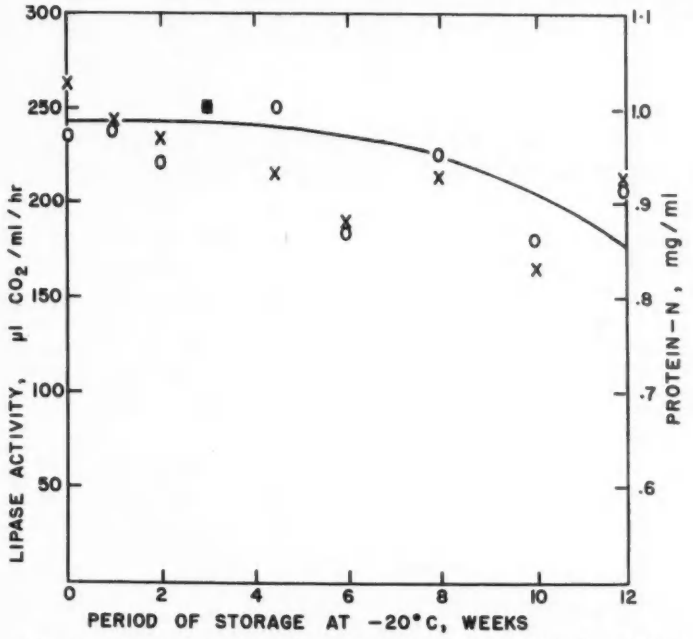

FIG. 2. Lipase activity (o—o) and soluble protein (x—x) in lingcod fillets after storage of the flesh for various lengths of time at –20°C. All values are given per millilitre of enzyme preparation.

muscle fat in several species of fish suggests that a phospholipase may play the major role in the free fatty acid formation. The possibility of a phospholipase in lingcod muscle is now being investigated.

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The First Record of a Northern Blennioid Fish, *Plectobranchus evides* Gilbert (Family Stichaeidae), in British Columbia Waters

Four specimens of a blennioid fish of the prickleback family have been caught in two different localities in British Columbia coastal waters. The species is *Plectobranchus evides* Gilbert, and it constitutes a new record for this area. Three were caught by this Station's research vessel *Investigator No. I* while engaged in shrimp trawling on November 15, 1951; their standard lengths were 90, 102 and 105 mm. The location was in Stuart Channel on the east coast of Vancouver Island, adjacent to Ladysmith Harbour and at a depth of 47 fathoms on a mud bottom. On June 23, 1954, a fourth specimen 121 mm standard length, was taken in a shrimp trawl towed by the vessel *Yuri M* to the north of Tsowwin Narrows in Tahsis Inlet (west coast of Vancouver Island). This specimen, collected by Mr G. V. Dubokovic, came from a depth of 65 to 71 fathoms where the bottom was composed of mud and shell.

The following description has been prepared in the form used by Clemens and Wilby (1946).

TWO-SPOTTED PRICKLEBACK, *Plectobranchus evides* Gilbert, 1890.

Body very slender, elongate, moderately compressed; the depth nearly constant throughout, about one-eleventh of the length (Fig. 1). *Head* rather long, 4.7 inches

FIG. 1. Two-spotted prickleback, *Plectobranchus evides* Gilbert, taken June 23, 1954, in Tahsis Inlet. Total length of this specimen, 135.5 mm or nearly 5⅜ inches.

standard length, extending posteriorly well beyond origin of dorsal fin; *mouth* terminal, lower jaw included; *maxillary* reaching middle of orbit; *upper jaw* with a broad inner band of minute teeth in front and on sides, the outer series enlarged, two in front canine-like; *lower jaw* with teeth similar to outer series above, forming a patch in front, two of them being enlarged and canine-like; *vomer and palatines* with bands of small teeth; *eyes* large, orbit 3.8 in head, longer than snout; *snout* short, posterior nostril with a short flap; *gill membranes* united, joined to isthmus anteriorly with definite free fold posteriorly. *Pores* on head large, a series of 5 running backward from each eye, the two series joined by a cross series of 3 on occiput, a single pore on top of head in a line between posterior margin of orbits,

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2 beneath anterior portion of eye, a series of 8 following lower contour of preopercle and mandible.

Fins: *dorsal* (1) LIV to LVI, origin of dorsal well forward, first dorsal spines short but fully united by membrane, longest spine 4 in head; membrane of last spine reaching base of upper caudal rays; *anal*, II, 34 to 36, origin in advance of middle of body, under 19th to 21st dorsal spines, 2 short sharp spines, rays with terminal third free from membrane, last anal ray connected with base of lower caudal ray; *pelvics* I, 3, well developed, thoracic; *pectorals* with lowermost rays lengthened, their tips free from membrane; caudal short, rounded.

Lateral line faint, straight, without visible pores. *Scales* cycloid, small, covering body including nape and cheeks. *Colour* dusky olive above; lighter below; sides crossed by about 25 narrow white bars, narrower than interspaces; 3 equidistant dark blotches near back, each double, the two halves occupying contiguous interspaces between white bars; branchiostegal membrane dark; pectorals white at base, the distal half black, margined with white; ventrals white; dorsal fin with alternating oblique white and blackish bars, two black roundish spots on posterior marginal portion of fin; caudal fin whitish at base, then dusky to black, margined with white; anal light at base, black at edge of membranes, the free tips of rays white.

Length, up to 5⅜ inches (to tip of tail).

Distinguished by the two black spots on posterior margin of dorsal fin; the alternating oblique white and blackish bars on dorsal; the abruptly lengthened lower rays of pectoral fins; the dorsal with 54 to 56 spines; the anal with 2 spines and 34 to 36 rays; and about 25 white bars across the body.

This species is placed in the family Stichaeidae. The common name for fishes in this family has been changed recently from "northern blenny" to "prickleback" (Wilimovsky, 1954, p. 287). For *Plectobranchus evides* Gilbert, the common name "two-spotted prickleback" is suggested.

Range, southern California (Barnhart, 1936) to Vancouver Island, British Columbia.

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A Record of the Anomuran Crustacean *Emerita analoga* (Stimpson) from British Columbia

On June 23, 1959, Drs D. B. Quayle and W. E. Ricker found many "sand crabs", *Emerita analoga* (Family Hippidae), on the sandy beach bordering Wickaninnish Bay (Long Beach), west coast of Vancouver Island. As far as known, there is no previous record of *E. analoga* from British Columbia. Banner and McKernan (1943: *Science*, 97:119) reported that the range of the species was from Kalalock Beach, Washington, to San Bartolomé Bay, Baja California; and in the southern hemisphere from Peru to Chile.

On Long Beach, the sand crabs were buried in a bed about 150 feet inshore from the low water mark. Presence of the crustaceans was indicated by small V-shaped ridges on the surface of the sand. The twenty-three specimens collected were all females, with carapace lengths from 14.3 to 19.5 mm. All but three were carrying eggs which had been extruded recently.

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